CANMET

Canada Centre for Mineral and Energy Technology

Centre canadien de la technologie des minéraux et de l'énergie

Mining Research Laboratories

Laboratoires de recherche minière

Energy, Mines and Resources Canada

Énergie, Mines et Ressources Canada

Canada

THE ENERGY OF OUR RESOURCES · THE POWER OF OUR IDEAS

L'ENERGIE DE NOS RESSOURCES · NOTRE FORCE CREATRICE

ANALYSIS OF TIME AND FREQUENCY DOMAIN OF MINING INDUCED SEISMICITY AT KIDD CREEK MINE, ONTARIO

L. LAVERDURE

MRL 92-079(TR) APRIL 1992

This document is an unedited internal report prepared primarily for discussion and internal reproduction purposes. It does not represent a final expression of the opinion of the Canada Centre for Mineral and Energy Technology (CANMET).

Ce document est un rapport provisoire non révisé et rédigé principalement pour fin de discussion et de documentation interne. Il ne représente pas l'expression définitive de l'opinion du Centre canadien de la technologie des minéraux et de l'énergie (CANMET).

114 pp

MICROMEDIA

92-07762/

Analysis of Time and Frequency Domain of Mining Induced Seismicity at Kidd Creek Mine, Ontario

L. Laverdure*

ABSTRACT

The complex structural geology and deep mining level at the Kidd Creek Mine leads to increased levels of rockburst activity. A full waveform analysis of mining induced seismicity was therefore proposed to Kidd Creek Mine of Falconbridge Ltd. by CANMET. Five hundred and ninety-one events were recorded by a portable seismograph (PDAS) between March and September 1991. Forty events were retained for analysis, consisting of mining induced seismic events and a few blasts .

Three types of waves were recorded: P- or compressional, S- or shear, and surface waves. The latter are rarely recorded in mining seismicity because the sensors are usually glued to bedrock. However, surface wave propagation at Kidd Creek was recorded by a triaxial accelerometer placed on the concrete floor of a storage room.

Thirty-nine of the forty events recorded by the PDAS were also recorded by the Kidd Creek MP-250 microseismic system, and located using CANMET's BBLOCK program. Sixteen of these events were also located using the simplex algorithm. The two source location methods agree to within a few meters. On June 27 1991, a major rockburst of magnitude 2.6 Mn was recorded by the PDAS, (which because of a power failure, was not recorded by the MP-250). The source location was estimated to be 441 meters away from the PDAS.

The source mechanism had a significantly higher shear than compression-dilatation component as illustrated by the energy content of the P- and S-waves. The magnitude of

---

Key words: Mining seismicity; Rockburst; Waveform analysis.

*Research Scientist, Elliot Lake Laboratory, CANMET, Energy, Mines and Resources Canada, Elliot Lake, Ontario.

events was estimated from the energy values with the events greater than 1.4 Mn being confirmed by the Geological Survey of Canada in Ottawa.

An attempt to analyze the data in the frequency domain was made but due to short source-receiver distances, i.e., less than one kilometre, this analysis could not be performed. This was because the frequencies contained in the waves were higher than the maximum sampling rate and higher than the 200 Hz hardware filter cut-off frequency, intrinsic to the PDAS.

However, recognition of this fact would enable a reasonable analysis of data to be done for any future study either by placing the PDAS further away from the seismic activity or by designing a more adequate instrument.

Analyse temporelle et fréquencielle de la séismicité induite à la mine Kidd Creek, Ontario

L. Laverdure*

RÉSUMÉ

La géologie structurale complexe et la profondeur des niveaux déjà minés à la Mine Kidd Creek ont entraîné un accroissement du nombre de coups de toit. CANMET a donc proposé à la mine Kidd Creek, Falconbridge Ltée, d'étudier les ondes séismiques induites par le minage. Cinq cent quatre-vingt-onze événements ont été enregistrés par un sismographe portatif (PDAS-100) entre les mois de Mars et Septembre 1991. Quarante événements constitués de sautages et de séismicité minière induite ont été retenus pour fins d'analyse.

Trois types d'ondes ont été enregistrés: P- ou de compression, S- ou de cisaillement, et de surface. Ces dernières sont rarement observées en séismicité minière puisque les senseurs sont habituellement collés au roc. Cependant, la propagation des ondes de surface à Kidd Creek a été possible parce que l'accéléromètre triaxial avait été placé sur un plancher de béton recouvrant un matériel non consolidé.

Trente-neuf des quarante événements enregistrés par CANMET ont aussi été enregistrés par le système MP-250 appartenant à la mine, et localisés par le programme BBLOCK de CANMET. De plus, seize de ces événements ont été localisés par le programme SIMPLEX. Les résultats des deux méthodes concordent à l'intérieur de quelques mètres. Le 27 Juin 1991, un important coup de toit de magnitude 2.6 Mn a été enregistré par le PDAS, mais non par le MP-250 puisque la mine a subi une panne de courant majeure. Dans ce cas, une estimation de la localisation de la source évaluée par la différence des temps d'arrivée des ondes P et S a permis de conclure que l'origine du coup de toit se trouvait à 441 mètres de distance du PDAS.

Mots clés: Séismicité minière; Coup de toit; Analyse des ondes.

Chercheur scientifique, Laboratoire d'Elliot Lake, CANMET, Energie, Mines et Ressources, Canada, Elliot Lake, Ontario.

Le mécanisme de la source comporte une portion plus importante de cisaillement que de compression-dilatation tel qu'illustré par l'énergie contenue dans les ondes P- et S-.

La magnitude des événements a été évaluée à partir de l'énergie contenue dans l'onde totale. Les événements de magnitude supérieure à 1.4 Mn ont été confirmés par le réseau séismique de la Commission Géologique du Canada.

L'analyse des données dans le domaine des fréquences s'est avérée impossible. Les distances source-récepteur étant relativement petites, i.e moins d'un kilomètre, le contenu en fréquence des ondes était supérieur au taux d'échantillonnage maximum et à la fréquence de coupure du filtre, intrinsèques au PDAS.

Cependant, la reconnaissance de ce fait nous permettra d'effectuer des analyses ultérieures dans le domaine des fréquences avec un tel séismographe en s'assurant que ce dernier soit placé à une plus grande distance de l'activité séismique. De plus, un nouveau séismographe portatif peut maintenant être mis au point puisque les caractéristiques des ondes sont mieux définies.

Contents

ABSTRACT i
RESUME iii
1. INTRODUCTION 1
2. GEOLOGICAL SETTING 1
3. MINE PLANS 3
4. DESCRIPTION OF THE INSTRUMENT 3
4.1 Portable Seismograph 3
4.2 The Accelerometers - PA-20 5
5. TIME ANALYSIS 6
5.1 Wave Types 6
5.2 Source Location 8
5.2.1 The Block Algorithm 8
5.2.2 The Simplex Algorithm 9
5.2.3 Error Calculation 9
5.2.4 Source Location Analysis 10
5.3 June 27 Event 11
5.4 Source Mechanism 14
5.5 Magnitude Evaluation 17
6. FREQUENCY DOMAIN 18
6.1 General Parameter Definitions 18
6.2 Attempt at Frequency Domain Analysis 23
7. CONCLUSION 32
8. ACKNOWLEDGEMENTS 34
9. REFERENCES 34
APPENDIX A - Digized Mine Plans A-36
APPENDIX B - Mine Geophone Coordinates B-50
APPENDIX C - Source Location - Block Algorithm C-53
APPENDIX D - Source Location - Simplex Algorithm D-90

Tables

1. Energy Partition of the recorded window 15
2. Magnitude evaluation 19

Figures

1. Surface geology at Kidd Creek Mine 2
2. Location of the portable seismograph, PDAS, in a storage room on 800 level 4
3. Wave types recorded by the PDAS: compression P-, shear S-, and surface waves .. 7
4. June 27 rockburst accelerograms for the north-south, east-west and z orientations 12
5. Hypocentral distance based on the difference in P- and S- arrival times for the June 27 rockburst 13
6. Full waveform analysis program flow chart 22
7. S-wave spectral density for the event on May 24 at 04:56, east-west, north-south and z orientations 24
8. S-wave spectral density for the event on June 14 at 12:05, east-west, north-south and z orientations 25
9. S-wave spectral density for the event on June 18 at 22:54, east-west north-south and z orientations 26
10. S-wave spectral density for the event on July 29 at 09:20, east-west north-south and z orientations 27
11. S-wave spectral density for the event on July 30 at 10:55, east-west north-south and z orientations 28
12. S-wave spectral density for the event on July 11 at 12:57, east-west north-south and z orientations 29
13. S-wave spectral density for the event on July 15 at 19:59, east-west north-south and z orientations 30
14. S-wave spectral density for the event on July 17 at 00:15, east-west north-south and z orientations 31

1. Introduction

In early 1991 CANMET proposed a two-month feasibility study on the full waveform analysis of mining induced seismicity to Mine Management at Kidd Creek Mine of Falconbridge Ltd. A portable seismograph was installed underground, which recorded 591 seismic events between the months of March and September 1991. Forty events were selected for the present analysis.

2. Geological Setting

Kidd Creek Mine is located 27 km north of Timmins, Ontario, on the west side of the Abitibi Greenstone belt. The massive sulphide orebody has produced??? zinc, copper, lead and silver since 1965 (Walker and Mannard, 1974), starting with an open pit followed in 1973 by underground mining (Yu, 1980).

The orebody strikes north and dips approximately 80° east. The complex structural geology is dominated by two major faults: the north shear, which is near vertical and dips eastward, and the north-south shear, which dips 75° towards the east (Figure 1). The orebody is intensely and inhomogeneously deformed. Below 2800 level the major principal stress is nearly E-W within a subhorizontal plane. The minor principal stress is about one third the major principal stress and nearly vertical (Yu and Quesnel, 1984). Ground stresses are similar to those observed in other deep hard rock mines in Northern Ontario, with the vertical stress equivalent to the overburden load, and the horizontal stresses higher than the vertical stress. The horizontal/vertical stress ratio is between 1.2 and 2.2 (Arjang, 1987).

Backfill has been used for ground support at the mine. Backfill, as a result of its composition, low density and low stiffness, affects the propagation velocity of the seismic waves.

Seismicity has been monitored since 1980. In the initial study in the mine, the relationship between peak particle velocity (ppv) after blasting and the charge weight/delay was studied

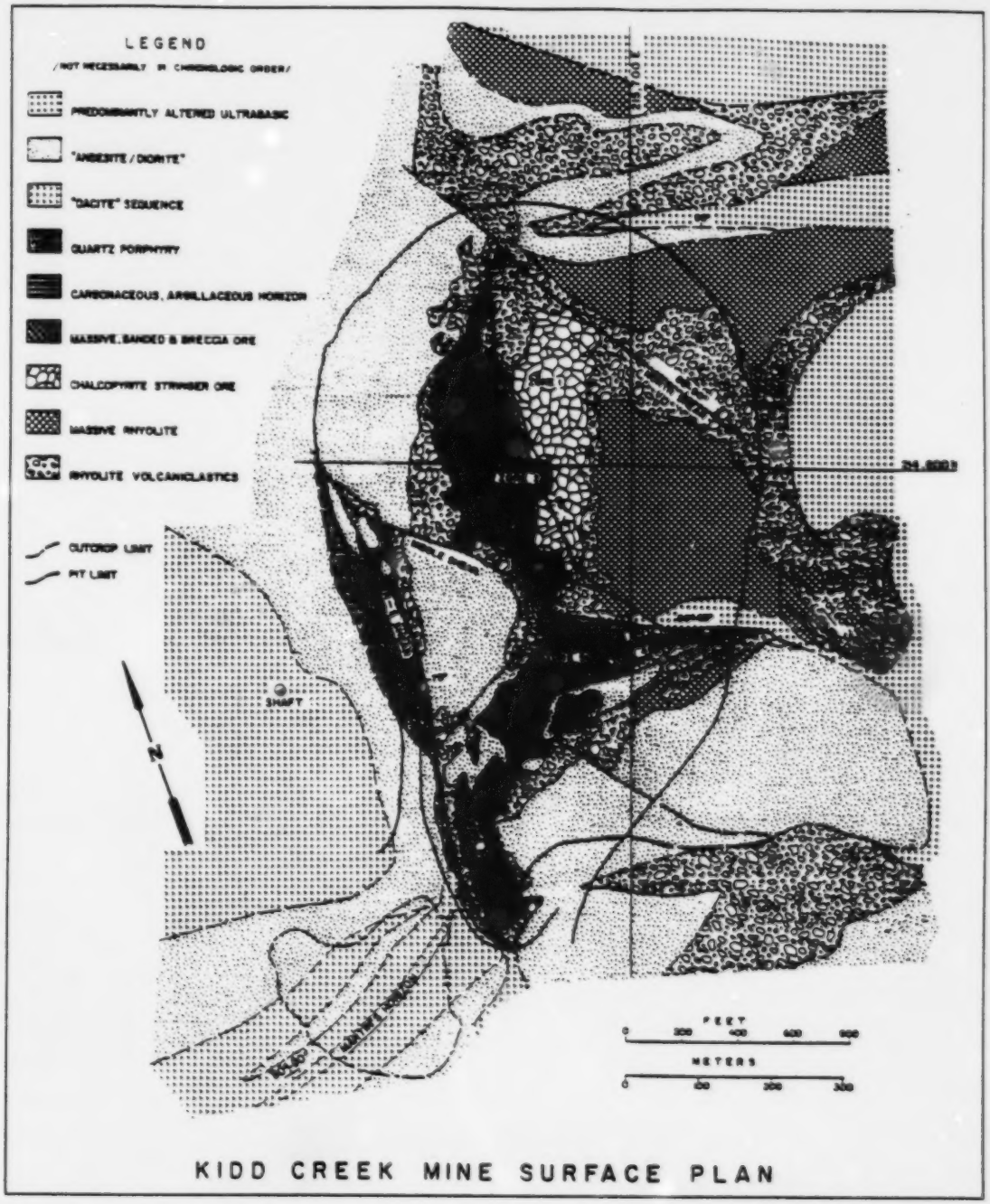


Figure 1 - Surface geology at Kidd Creek Mine,
(after Walker and Mannard, 1974).

(Yu, 1980).

In 1988, because of the greater depth of mining and the increased possibility of rockburst occurrence, a MP-250 system from Electro-Lab was installed to record arrival times of seismic waves using a widespread array of uniaxial geophones.

3. Mine Plans

The digitized versions of the original geological and mining plans supplied by the mine are shown in Appendix A. On each level, the orebody and the principal geological units i.e., quartz porphyry, andesite-diorite, massive sulphide, copper, and the mine workings such as the shaft, ore passes, ventilation and backfill raises, backfilled areas, the MP-250 geophones, and the rockburst source locations were plotted on the mine plans.

4. Description Of The Instrument

4.1 Portable Seismograph

A portable seismograph was required that would operate in rugged areas and under extreme conditions of temperature and humidity, and also be capable of capturing full waveforms. The Teledyne Geotech PDAS-100 designed for earthquake analysis meets these requirements and one was available at CANMET. In response to the initial request from Kidd Creek Mines in March 1991, this instrument was installed in the mine and was used for seven months. It was the only instrument that recorded the June 27, 1991 seismic event.

The PDAS was installed on 800 level in a locked storage room away from mining activity (Figure 2) with the geophone box containing the three accelerometers placed directly on the concrete floor. In order to increase the coupling between the sensor and the floor, sand bags were placed over the geophone box.

The rechargeable batteries of the PDAS were continuously charged at the mine site to avoid

Figure 2 - Location of the portable seismograph, PDAS, in a storage room on 800 level.

interruption of data acquisition by power failure.

An IBM computer acted as a dedicated control system for the PDAS and was used to set the recording parameters, the calibration, the clock synchronisation, and the data transfer from the PDAS memory to the computer. The data acquisition parameters were selected through a menu-driven program on the computer.

The triggering mechanism used is a function of the voltage level of an event relative to noise voltage. After establishing the level of the adjustable threshold, the data are digitized at a maximum rate of 1,000 samples per second per channel. The processing includes the application of an anti-aliasing filter. The filters consist of one high-pass 1 pole 0.01 hertz, to remove the DC offset, and one anti-alias analog 6 pole or 36 db/octave with a 200 hertz cutt-off frequency (120 db rejection from 0.8 Nyquist to Nyquist frequency). The pre-event time was set at 0.5 sec. A window length of 3 seconds was maintained for the present analysis. The post-event length was set between 0 to n seconds, with the value of n being the remaining memory space in the pre-selected time window.

The preamplifier gain was set at 10 for each of the three channels. The low gain full-scale was set at ±2 volts. After some adjustment the triggering level was established at 6% higher than the noise level, i.e., ±0.12 V. The conversion factor between the acceleration amplitude and the output voltage is 0.00011963 m/sec^2.

The data were recorded and stored in the 4.5 megabyte static RAM memory. Because of the selected threshold level, sampling rate, and window length it was necessary for mine personnel to transfer the recorded data from the PDAS memory to DOS diskettes about once every two weeks, and forward them to CANMET for analysis.

4.2 The Accelerometers - PA-20

The sensor used with the PDAS was a surface triaxial accelerometer orthogonally oriented with x-axis - north south, y-axis - east west, and z-axis - vertical. The accelerometer PA-20

manufactured by Teledyne Geotech is based on three piezoelectric ceramics which could undergo a shock of 20 g peak (g: earth acceleration of 9.78 m/sec^2). The sensitivity is 5 volts/g with a full-scale output of ±2.0 g. With a clipping level established at ±2.2 g, the geophone would be saturated by strong events.

As the natural frequency of the geophone is 1250 Hz and the PDAS maximum sampling rate is 1000 Hz, the system operates below its natural frequency hence eliminating resonance due to the accelerometers. The sensor output, without saturation, shows a flat response between 0.02 and 2000 Hz.

5. Time Analysis

5.1 Wave Types

Three principal wave types were registered by the PDAS as shown in Figure 3. The first wave is the compression or P-wave, followed by the shear or S-wave. In general, the S-wave amplitude was greater than that of the P-wave, which could be attributed to the source mechanism providing more shear movement than compression-dilation. The shear wave arrived at the geophone shortly after the compression wave because the S-wave velocity on average is 2400 m/sec slower than the P-wave. A third wave type which was recorded by the system and is not normally recorded by CANMET'S other permanent underground systems shows a large amplitude with a low frequency. These waves are probably surface waves which are characterized by a much lower velocity, a higher amplitude, and a lower frequency content (Figure 3). The surface waves develop in loose unconsolidated materials containing voids, such as earth, sand, gravel, etc., i.e., within materials with high impedance contrast. The surface waves were recorded because the geophone was placed on a concrete floor which covered small rocks and loose material. In CANMET'S permanent installation the sensors are directly coupled to the rock by being grouted to it, and the generation of surface waves is eliminated. However, in seismic surveys, as the geophones are generally coupled to the overburden, the seismograms often incorporate this type of wave.

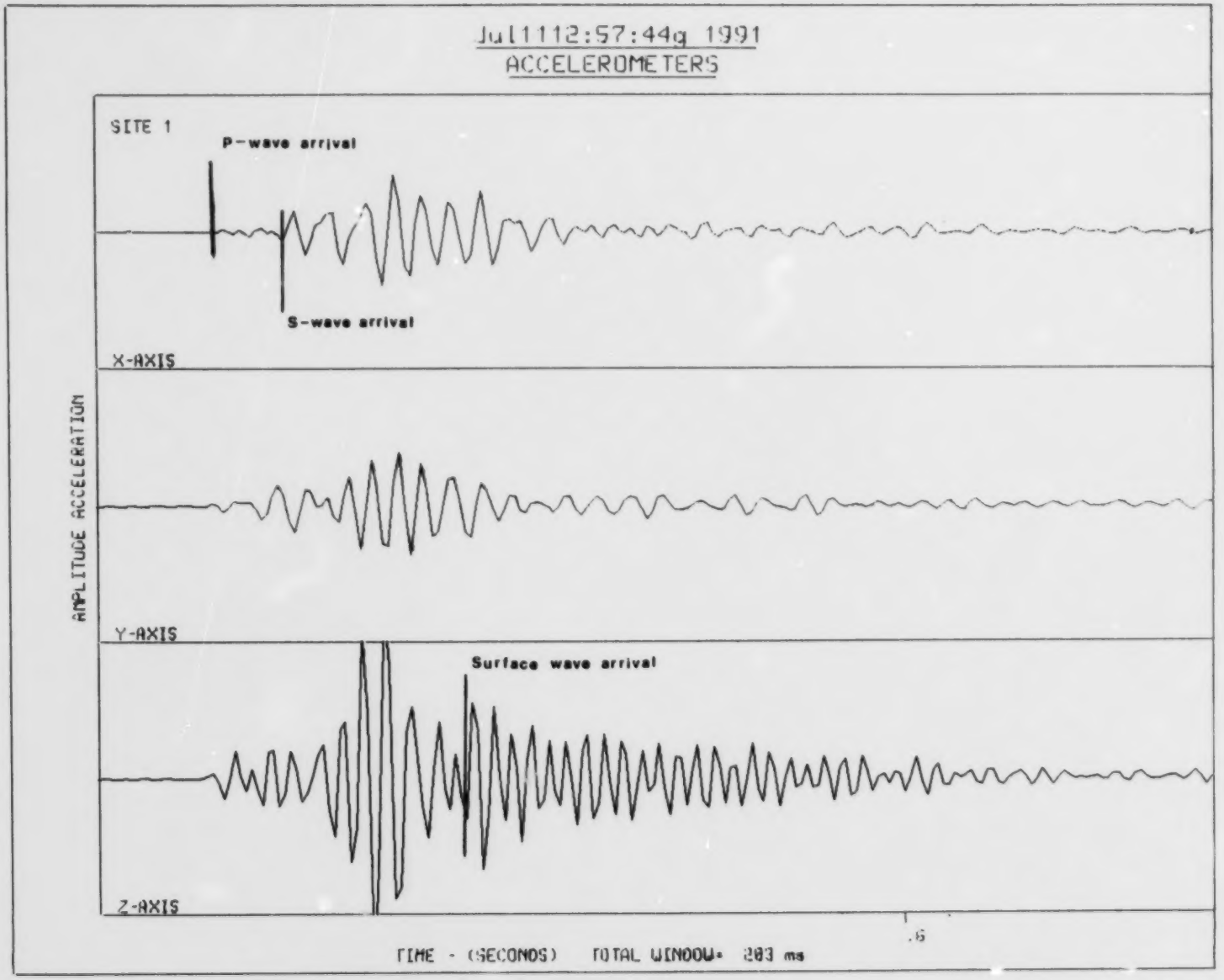


Figure 3 - Wave types recorded by the PDAS: compression P-, shear S-, and surface waves.

5.2 Source Location

Between March and September 1991, over 591 mining-induced seismic events were registered by the PDAS. Before proceeding with the full analysis, most of the blasts and all the spikes and noisy signals consisting of electrical, mechanical or human noise, were deleted manually, and forty seismic events were retained for full waveform analysis. The location of the seismic sources was estimated based on the channel sequence recorded by the MP-250 system, consisting of 64 uniaxial geophones, and their underground coordinates (Appendix B). Two algorithms for source location were deployed: i) the block, ii) the simplex.

5.2.1 The Block Algorithm: The analysis consists of defining a large initial block and calculating the objective function at the vertices and central point of the defined block:

$$F(x,y,z) = \sum_{i=1}^{n} ((t_i - t_1) - (t_i^c - t_1^c))^2 \qquad (1)$$

$$\text{where:} \quad t_i^c = (((x-a_i)^2 + (y-b_i)^2 + (z-c_i)^2)^{1/2}) / v_i \qquad (2)$$

where, F(x,y,z) = objective function

(x,y,z) = vertex coordinates

n = number of geophones

t_i = time recorded by the MP-250 at the i-th geophone

t_1 = time recorded by the MP-250 at the first geophone

t_i^c = calculated travel time from the vertex source point to the i-th geophone

t_1^c = calculated travel time from the vertex source point to the first geophone

(a_i,b_i,c_i) = i-th geophone coordinates

v_i = velocity of the P- or S-wave arrival through the medium between the source and the i-th geophone.

The program determines the minimum value of the objective function which becomes the centre of a new block. In the present analysis a block of 200 m per side centered on the MP-250 source location has been used as a starting model. The iterative process continues until the block dimensions are as defined and a pre-set precision is reached i.e., 3 m (Niewiadomski, 1986).

5.2.2 The Simplex Algorithm: This methodology introduces a fourth variable in addition to the previous method. This variable is the travel time T_0, which is the time between the source and the first receiver (Gendzwill and Prugger, 1978). In this case the objective function is defined as:

$$F(x,y,z) = \sum_{i=1}^{n} ((t_i - t_1 + T_0) - t_i^c)^2 \qquad (3)$$

where, $F(x,y,z)$ = objective function

(x,y,z) = vertex coordinates

n = number of geophones

t_i = time recorded by the MP-250 at the i-th geophone

t_1 = time recorded by the MP-250 at the first geophone

t_i^c = calculated travel time from the vertex source point to the i-th geophone

T_0 = travel time between the source and the first geophone triggered

The same kind of iterative procedure as used for the BBLOCK program is used to determine the minimum error.

5.2.3 Error Calculation: The error function ERS calculated for both programs (Appendix C and D) gives an idea of the difference between the calculated and recorded time. In fact, it is an estimate of the difference between theoretical and calculated source location as follows:

$$err = \left[\frac{\sum_{i=1}^{n} ((t_i^c - t_i) * v)^2}{(n-1)} \right]^{1/2} \qquad (4)$$

where: v = wave velocity of the P- or S-wave

The velocities used for the analysis were in meters per second, therefore, the error was calculated in meters.

5.2.4 Source Location Analysis: All 40 mining-induced seismic events selected were located by BBLOCK program. For the purpose of comparing the accuracy of both BBLOCK and SIMPLEX, 16 of the seismic events were selected for the SIMPLEX analysis. The two techniques were comparable in locating the source of the seismic events within 6 m. The same conclusion was reported by Hedley (1992). The results of BBLOCK and SIMPLEX analyses are listed in Appendix C and D, respectively. The programs allow the user to select the propagation wave velocity between the seismic event and each triggered sensor. For this study, constant velocities of the P- and S-waves were used: 6100 m/sec, and 3700 m/sec, respectively. The investigation by Sial (1989) on velocity of seismic waves at Kidd Creek mine indicates that there is a high degree of variability of wave propagation at the mine site. In this analysis, however, the constant velocity assumption is adequate since the location errors are kept relatively small, i.e., in the order of a few meters. It is suggested that, in any future study, the variation in S-wave velocity be quantified by a tomography study, providing the degree of variability of S-wave velocity and its incorporation in the source location analysis.

Both programs allow the interpreter to remove the doubtful geophones which recorded wrong arrival times. As mentioned in section 4.1 the triggering mechanism starts keeping the data in memory when it has reached a pre-established voltage level at each geophone. With the MP-250 system any trigger is considered as the real time for the P-wave to travel in a straight wavepath between the rockburst source and geophone. Then any false event

could have been triggered at any specific geophone by another local event, by another wave type in the waveform (such as S-waves) or even by another wave path which does not count for a direct P-arrival between the source and the geophone.

5.3 June 27 Event

On June 27 1991, a rockburst of 2.6 Mn was recorded at the mine (Figure 4). Unfortunately, this event occurred after a general power failure at the mine site and, as a consequence, the MP-250 was not operating, making the analysis of the source location of the event more difficult to evaluate. In view of no first arrival time data from the MP-250, an alternate method had to be deployed. This method evaluates the time difference between the S- and the P-wave arrivals, as a function of the distance to the hypocentre. Assuming an homogeneous and constant velocity medium the relationship time difference-distance is linear (Figure 5). In order to locate this event, all the events between March 6 and July 30 were plotted and a least square function was evaluated:

$$y = 7.24\,x + 86.42 \qquad (5)$$

where: y = hypocentre distance (meters)

x = S - P time difference (seconds)

According to this relationship the hypocentral distance for this rockburst would be 441 m away from the PDAS sensor. In order to define in which quadrant the event occurred, the polarities of the first arrivals on each channel x, y, z must be defined. This could be achieved by calibration, using the blasts as the source of energy, providing compressional waves. A number of blast experiments were conducted by the mine personnel to define this parameter. The conclusion reached was that positive polarities corresponded to a compression:

from south to north
from west to east
from bottom to top.

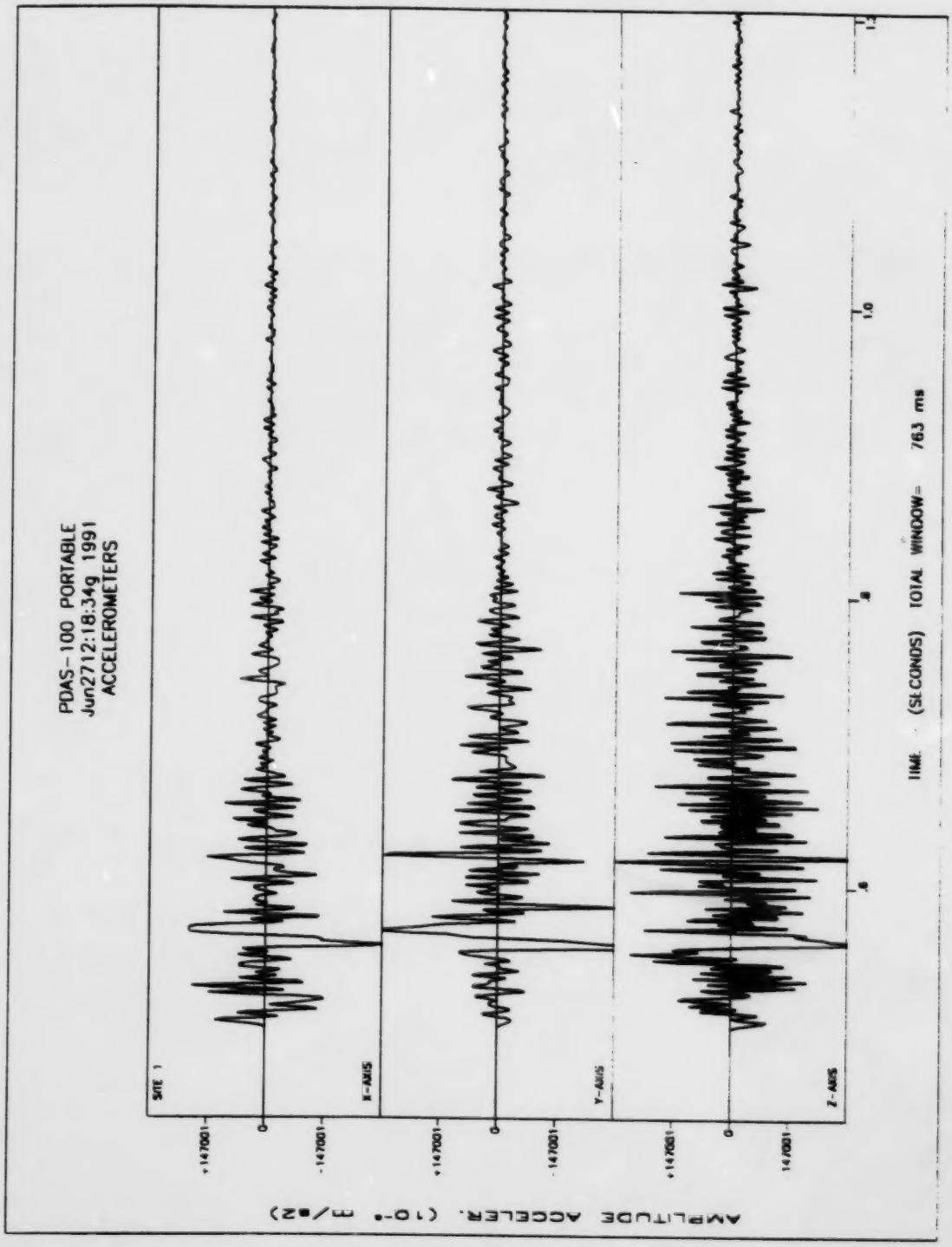


Figure 4 - June 27 rockburst accelerograms for the north-south, east-west and z orientations.

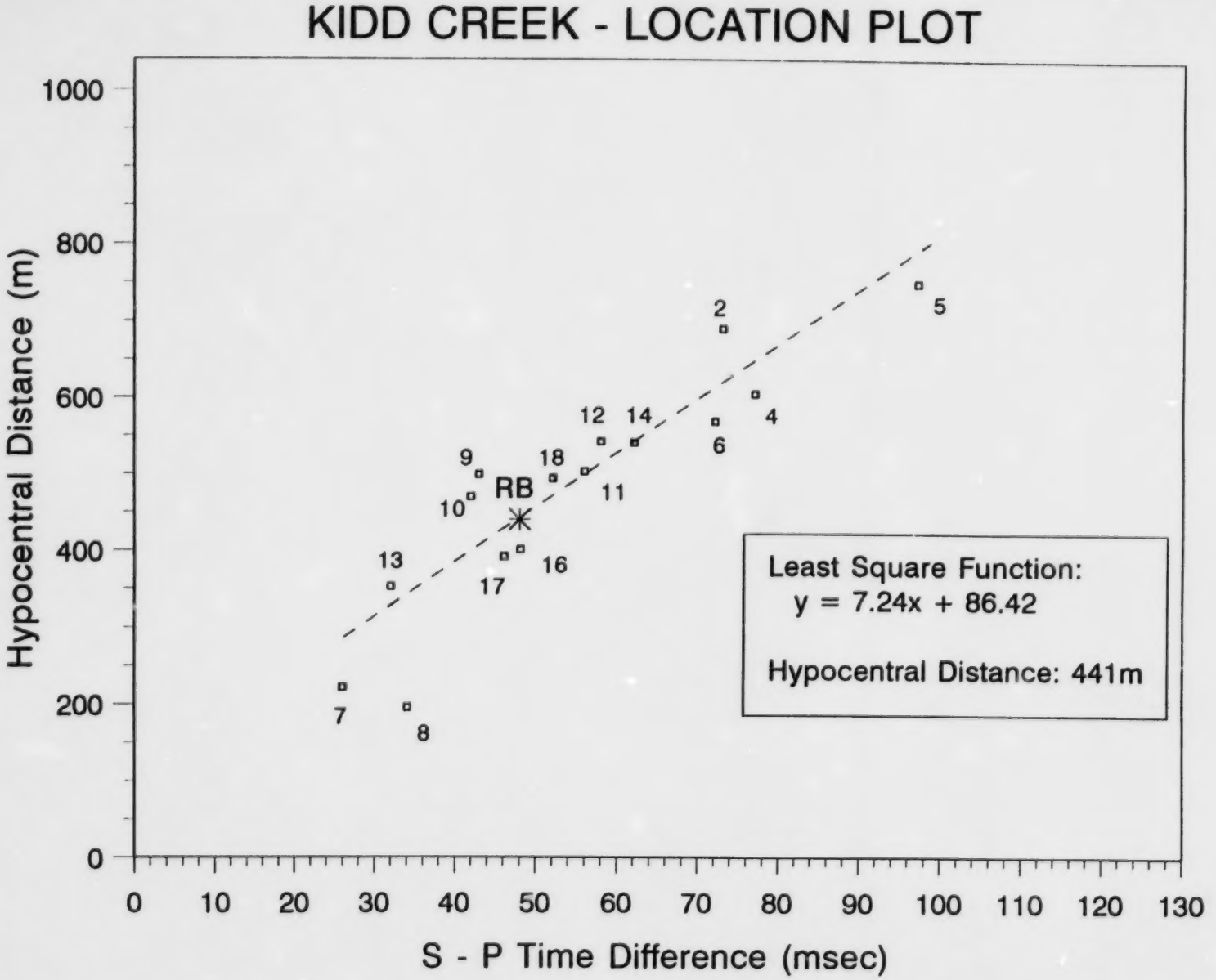


Figure 5 - Hypocentral distance based on the difference in P- and S-arrival times for the June 27 rockburst.

In accepting this conclusion, if a compressional event is assumed, the ground motion had occurred from south to north, east to west and bottom to top.

On the other hand the assumption of a compressional event, which is produced by a blast, does not reconcile well with the fact that only 11% of the energy corresponded with the compressional P-wave arrival (section 5.4). In other words, most of the total energy for induced seismic events (68%), produced the S- shear wave, as shown in Table 1. Consequently, the quadrant cannot be defined with the available information because too many non-realistic assumptions have to be made. This lack of conformity between the definition of the quadrant is difficult if not an impossible task, as too many invalidated parameters have to be employed in the deduction.

5.4 Source Mechanism

To determine the mechanism controlling the rock mass displacement, the energy content corresponding to the compression and the shear waves has been estimated (Table 1):

$$E_t = E_p + E_s + E_n \tag{5}$$

where: E_p = Energy contained in the P-wave

E_s = Energy contained in the S-wave

E_n = Energy contained in the noise recorded to the full extent of the recorded wave

The total energy E_t, in kilojoules, is calculated from the full waveform in the time domain:

$$E_t = 4\pi R^2 \rho \left(\alpha \int^{T_s} v_p^2 dt + \beta \int^{T_s} v_s^2 dt\right) \tag{6}$$

where: R = source-receiver distance (m)

ρ = rock density (kg/m^3)

Table 1 - Energy partition of the recorded window

DATE	TIME	DISTANCE (m)	E_T (KJ)	E_P (KJ)	E_S (KJ)	$\%E_P/E_T$	$\%E_S/E_T$
March 06	11:51	466	11	0	3	0	27
March 06	22:48	690	894	28	581	3	65
March 07	00:54	539	18	0	1	0	6
May 03	23:38	605	29747	2298	27253	8	92
May 04	00:15	749	5645	534	4957	9	88
May 21	22:54	569	1377	236	1108	17	80
May 23	21:32	222	11	0	3	0	27
May 24	04:56	196	58	0	1	0	2
May 29	22:54	499	13384	8823	4560	65	34
June 12	22:43	470	1421	blast			
June 14	12:05	503	17	2	12	12	71
June 17	23:27	542	381	41	313	11	82
June 18	22:54	353	8	1	4	12	33
June 27	04:29	541	139	16	95	11	68
June 27	12:18	442	saturated				
June 29	09:20	401	9	0	4	0	44
June 30	10:35	392	83	1	65	1	78

Table 1 - cont'd

DATE	TIME	DISTANCE (m)	E_T (KJ)	E_P (KJ)	E_S (KJ)	$\%E_P/E_T$	$\%E_S/E_T$
July 03	13:29	422	15	0	1	0	7
July 03	18:31	596	29	0	7	0	24
July 04	21:07	449	7	0	1	0	14
July 09	21:23	396	11	0	4	0	36
July 10	09:37	1463	121	4	31	3	26
July 10	10:40	755	64	1	28	2	44
July 10	12:57	521	230	40	50	17	22
July 11	12:57	967	41	0	14	0	34
July 12	23:54	570	saturated				
July 15	01:26	940	146	0	40	0	27
July 15	02:39	921	197	3	12	1	6
July 15	19:59	277	12	0	2	0	17
July 17	00:35	263	4	0	1	0	25
July 17	02:53	435	5	0	1	0	0.2
July 21	09:36	540	117	13	87	11	74
August 02	01:29	666	42	0	9	0	21
August 16	12:11	487	44	5	27	11	61
August 28	21:52	599	37230	6860	29881	18	80
Sept. 04	22:56	1174	4855	2668	2187	55	45
Sept. 13	23:51	686	2178	130	1988	6	91
Sept. 23	22:50	856	134707	115900	14187	86	10
Sept. 30	22:03	1467	95556	86630	6063	91	6

α = velocity of the compression P-wave (m/sec)

T_P = P-wave window (sec)

v_P = P velocity of the particle (m/sec)

β = velocity of the S-wave (m/sec)

v_S = S velocity of the particle (m/sec)

This energy formula was adapted for the computer processing by Hedley (1989) and the modified form is expressed:

$$E_t = 4\pi R^2 \rho \beta \sum_{P}^{W} v_S^2 \Delta t \qquad (7)$$

where, P is the start of the P-wave arrival time
W is the end of the recorded time window
with the other parameters defined earlier

In analyzing the 40 events (Table 1) the shear energy component of the wave is far greater than the compressional component. However, there is an exception to this rule in the case of four blasts of May 29, September 4, 23, and 30, in which the expanding movement related to explosion is reflected in the energy distribution. These energies were evaluated at the geophone site. Shear failure is thus much more common than pure compression or dilatation.

5.5 Magnitude Evaluation

In determining the magnitude of earthquakes, seismologists utilize the Nuttli formula (Nuttli, 1973) developed for events propagating in central and eastern North America, compared to the Richter scale used for California earthquakes. Hedley (1991) used the Nuttli magnitude evaluations in order to establish a correlation between the Nuttli scale and the energy contained in the S-waves for a known distance source-receiver. Now, the Nuttli magnitudes are evaluated for the seismic induced events in Northern Ontario mines

according to this equation:

$$\log E_s = 1.3Mn - 1.75 \text{ in Megajoules} \quad (8)$$

where: E_s = energy contained in the shear wave

Mn = Nuttli magnitude scale

The National Seismograph Network of the Geological Survey of Canada also records mining induced seismic events occurring in Ontario. In the Sudbury basin, for example the GSC will give a Nuttli magnitude evaluation for events bigger than 1.6 Mn.

From the 40 events, the strongest 13 events recorded by the PDAS were also recorded by the National Seismograph Network of the Geological Survey of Canada. For seven mining induced seismic events which were either not saturated on the PDAS nor blast events, the magnitude estimates evaluated by CANMET and the GSC correspond within ±0.3 Mn and since the GSC estimates their magnitude within ± 0.3 Mn of error margin, there is a good agreement between the two sets of evaluations (Table 2). Accepting the accuracy of the magnitude scale for large events using the PDAS records, and thus comparing with the National Network, it could be concluded that similar accuracy and conformity of magnitudes exists for smaller events. In the case of those events where one or more channels (out of the three axial system of the sensor) were saturated, the evaluation of energy content became difficult, hence, no magnitude values were determined. Similarly, in the case of blasts, when superimposition of waves emitted by a shot sequence occurred on the recording, the magnitude determination was not performed.

6. Frequency Domain

6.1 General Parameter Definitions

In order to study seismic waves, a user-friendly program for full waveform analysis was

Table 2 - Magnitude evaluation

DATE	TIME	DISTANCE (m)	CANMET Magnitude (Mn)	GSC Magnitude (Mn)
March 06	11:51	466	-0.2	
March 06	22:48	690	1.3	1.5
March 07	00:54	539	0.0	
May 03	23:38	605	2.5	2.2
May 04	00:15	749	1.9	2.0
May 21	22:54	569	1.4	1.4
May 23	21:32	222	-0.2	
May 24	04:56	196	0.4	
May 24	18:55	494	saturated	
May 29	22:54	499	2.2	2.0
June 12	22:43	470	1.5	1.4
June 14	12:05	503	0.0	
June 17	23:27	542	1.0	
June 18	22:54	353	-0.3	
June 27	04:29	541	0.7	
June 27	12:18	441	saturated	2.6
June 29	09:20	401	-0.2	
June 30	10:35	392	0.5	

Table 2 - cont'd

DATE	TIME	DISTANCE (m)	CANMET Magnitude (Mn)	GSC Magnitude (Mn)
July 03	13:28	422	-0.1	
July 03	18:32	596	0.2	
July 04	21:07	449	-0.3	
July 09	21:23	396	-0.2	
July 10	09:37	1463	0.6	
July 10	10:40	755	0.4	
July 10	12:57	521	0.8	
July 11	12:57	967	0.3	
July 12	23:54	570	blast	2.3
July 15	01:26	940	0.7	
July 15	02:39	921	0.8	
July 15	19:59	277	-0.1	
July 17	00:35	263	-0.5	
July 17	02:53	435	-0.4	
July 21	09:36	540	0.6	1.1
August 02	01:29	666	0.3	
August 16	12:11	487	0.3	
August 28	22:52	599	2.5	2.0
Sept. 04	22:56	1174	blast	2.0
Sept. 13	23:51	686	1.6	1.9
Sept. 23	22:50	856	saturated	1.7
Sept. 30	23:03	1467	blast	2.0

developed by CANMET (Figure 6). After entering the waveforms, the source location and P- and S-wave velocities, the program evaluates some basic parameters such as the energy, peak particle acceleration (ppa), peak particle velocity (ppv), peak particle displacement (ppd), source-receiver distance, azimuth and emergence angles between the source and the receiver. The user can also define the P- and S-wave arrival times as well as the window on which the Fast Fourier Transform (FFT) would be performed.

For the frequency domain analysis, first the FFT is performed and the program illustrates the graph of the spectral density i.e., the amplitude displacement spectrum versus the frequency. The user defines the plateau and the slope for each axis of the event. Thereafter, the program calculates the corner frequency, the source radius, the seismic moment and the stress drop. All these parameters are evaluated according to Brune's model (Brune, 1970 and 1968) where triaxial data are essential. In the next paragraph each of the above parameters is briefly defined.

The **corner frequency** is related to the frequency at which the attenuation of the wave starts. The shorter the distance between the source and the receiver, the higher the corner frequency. The further the waves travel the lower their frequency content will be. The value of the corner frequency is also a function of the material traversed. For example, the corner frequency will be higher if the waves travel in a competent volcanic rock than if they travel in a soft, fractured sedimentary environment. The corner frequency is also inversely proportional to the time length of an event, i.e., if the event is caused by a true impulse, there will be no corner frequency and only a plateau. The **plateau** illustrates all the frequencies for which there is little attenuation between the source and the receiver. It indicates the particle displacement at the receiver which is a function of the event magnitude and source-receiver distance. The value of the **slope** is related to the attenuation factor of the medium in which the waves travel. In a perfectly elastic, homogeneous, and isotropic medium the slope, for each of the three axes, is -2.0. The **source radius** is an indication of the size of the rock mass movement. The **seismic moment** is related to the strength of the event, i.e., what kind of counter-moment has to be applied to stop the rock displacement? Finally, the **stress drop** is an evaluation of the amount of stress released

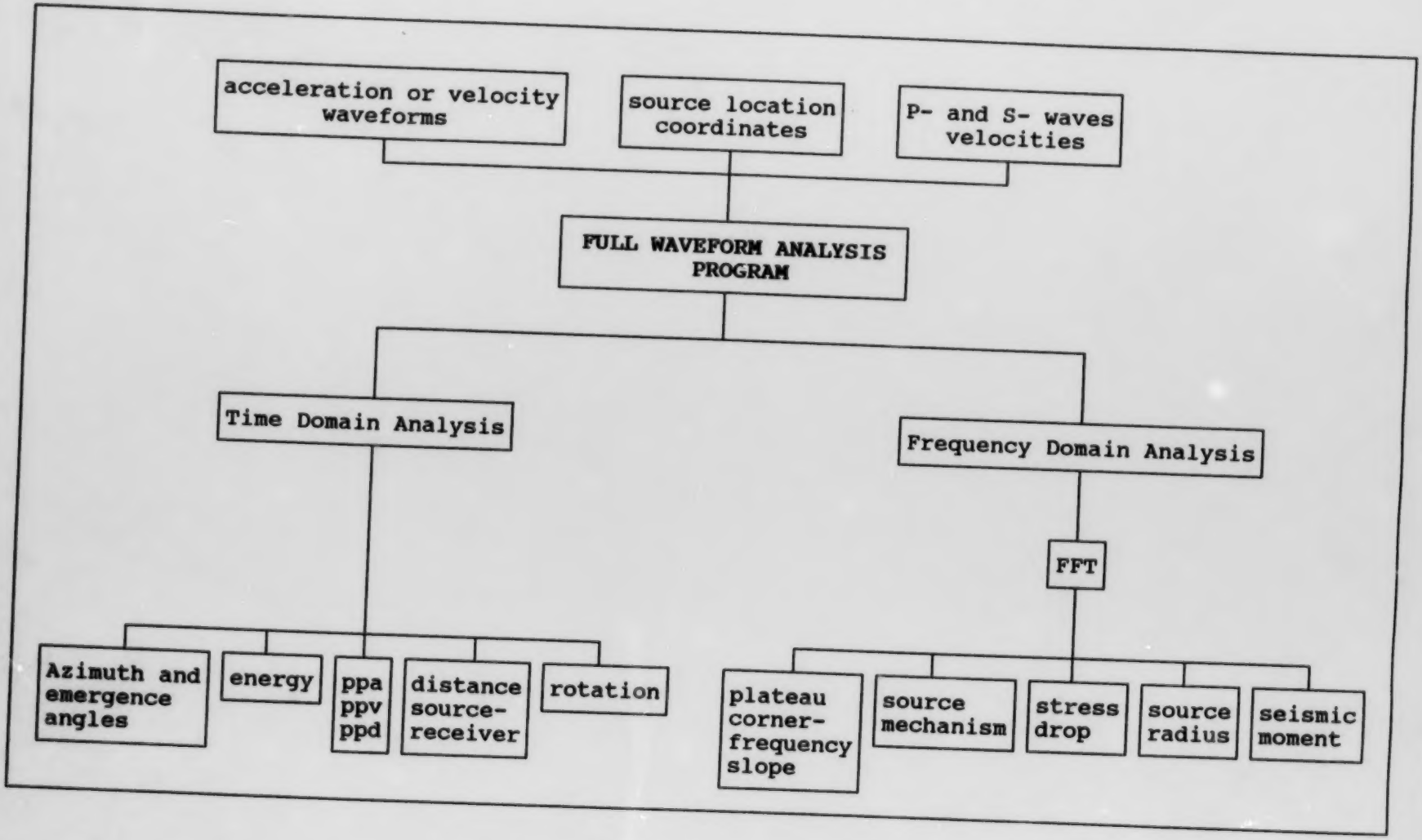


Fig. 6 - Full waveform analysis program flow chart.

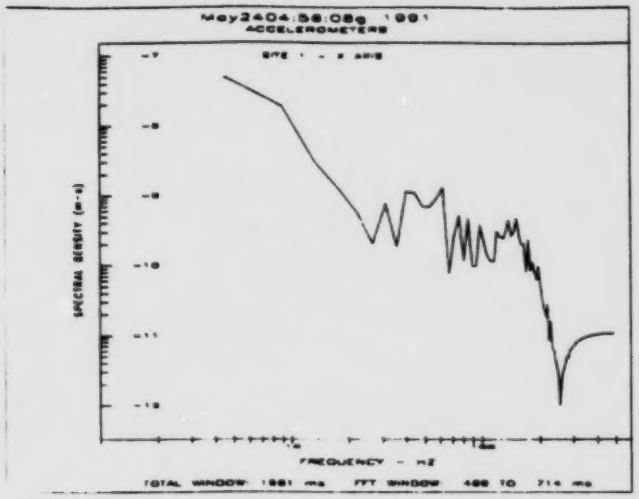
during the seismic event.

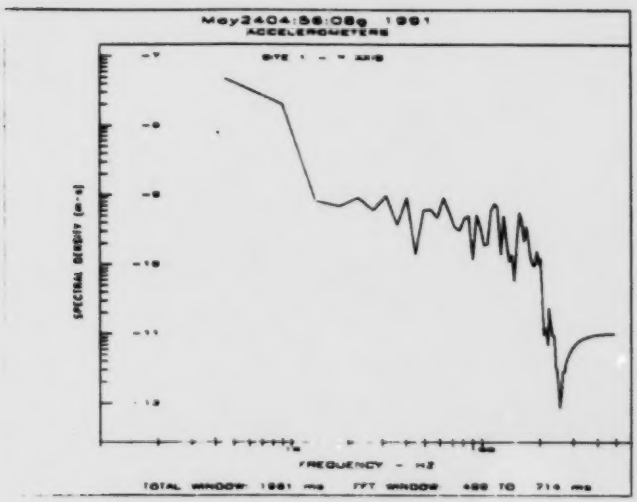
6.2 Attempt at Frequency Domain Analysis

Plouffe successfully analyzed the full waveforms of the seismic events recorded with the portable seismograph at Creighton Mine (Plouffe, 1990). The PDAS was placed on surface at an average distance of 2 km from the recorded seismic events. No surface waves were recorded mainly because the geophone was placed directly on an outcrop.

The same system was used at Kidd Creek Mine where some 591 seismic events were recorded between March and September. The proximity of the geophone to the source of seismic events prohibited analysis in the frequency domain to be carried out.

The problem arises from the hardware filters and the maximum sampling rate, which are intrinsic to this portable seismograph. The underground location chosen for PDAS was some 200-600 m away from the source of seismic events. This geometry gives rise to a high frequency content of the wave (see section 6.1). The maximum practical sampling rate is approximately four times the filter cut-off frequency, or 800 Hz, with a hardware filter of 200 Hz (Brigham, 1974). With a lower sampling rate, data aliasing, or distortion, would be introduced by the filter and the result would be meaningless. Since the PDAS was designed for earthquake studies where the outlet is placed far from the hypocentre and the frequencies contained in the waves are relatively low, the choice of 1,000 Hz maximum sampling rate with the 200 Hz (or 300 Hz available from Teledyne Geotech) hardware filter is appropriate. In rockburst studies, and specifically at Kidd Creek Mine, 70% of the recorded waves contain frequencies higher than the filter cut-off point (Figures 7-14). Moreover, the 200 Hz filters were designed to start cutting off the frequencies at 175 Hz (and not at exactly 200 Hz), and since they are not completely stable with time (Frequency Devices Corporation, 1986), a variation of ±3% in the frequency cut has been observed. As a result, the data after 160 Hz are not always reliable i.e., the frequency response could be influenced by the hardware and thus be artificial (Figures 7-14). Thereafter, the slope could be a characteristic of the filter instead of reflecting the rock parameters. Hence, the filters





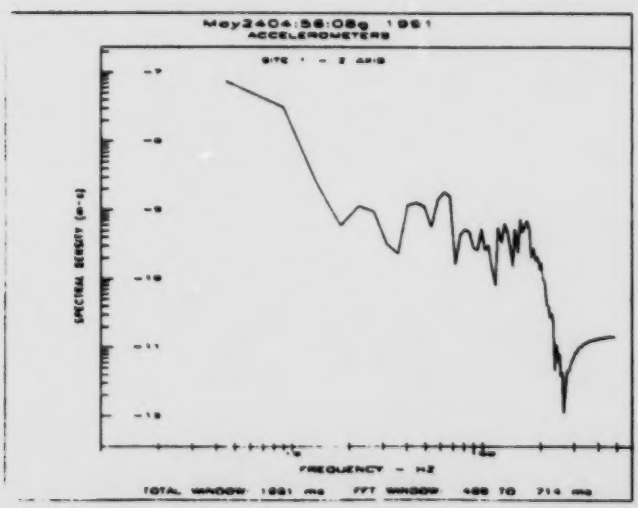


Figure 7 - S-wave spectral density for the event on May 24 at 04:56, east-west, north-south and z orientations.

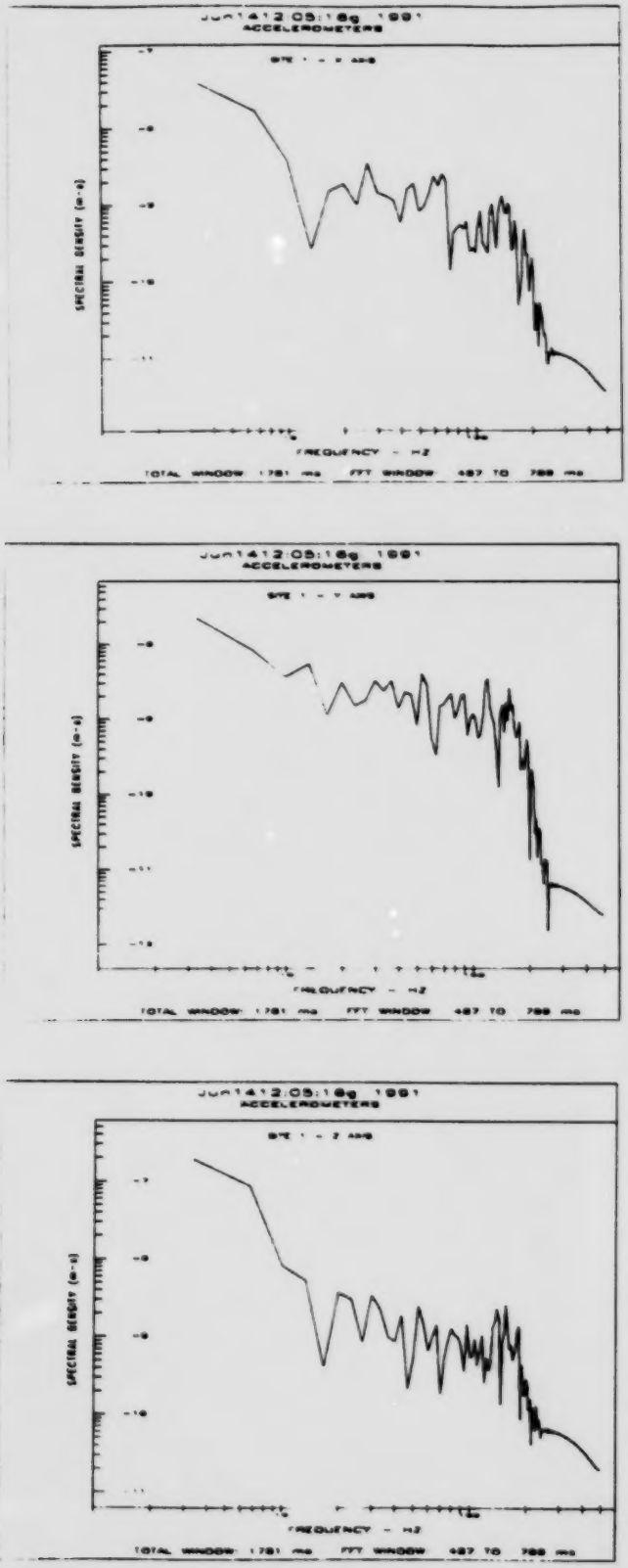


Figure 8 - S-wave spectral density for the event on June 14 at 12:05, east-west, north-south and z orientations.

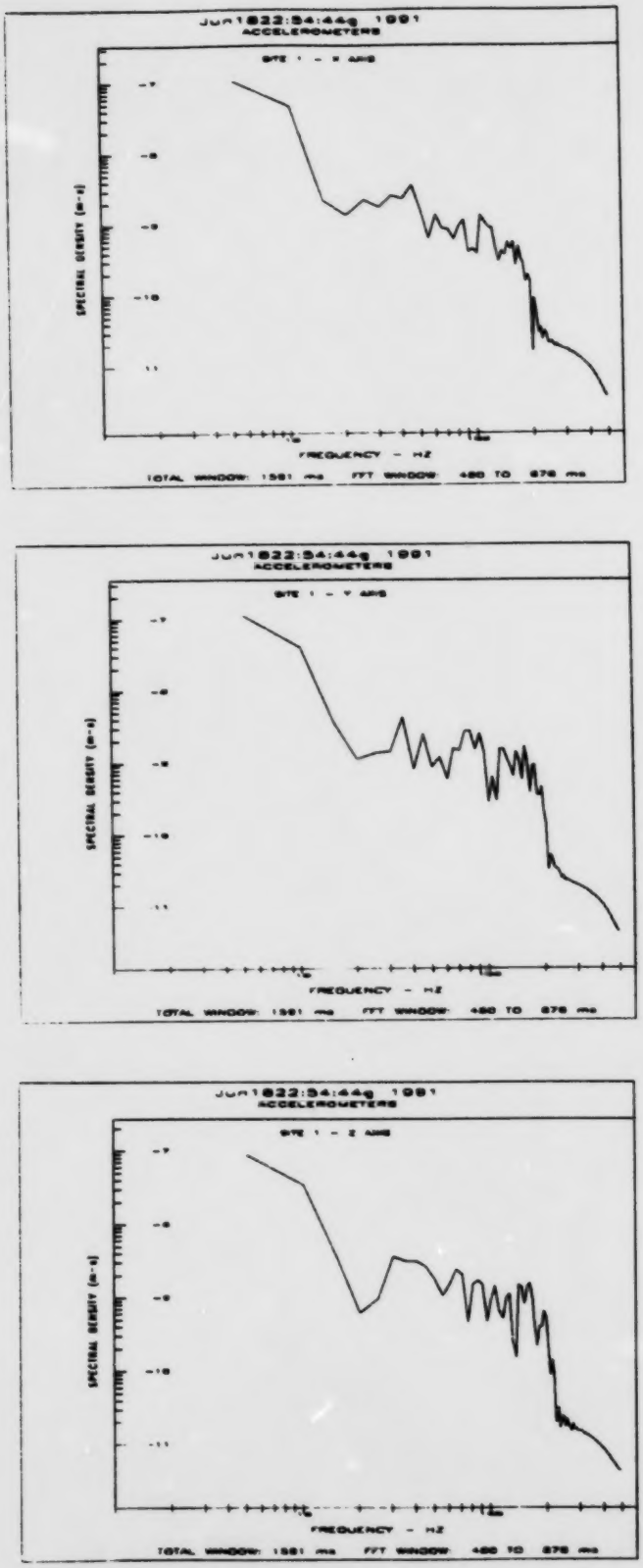
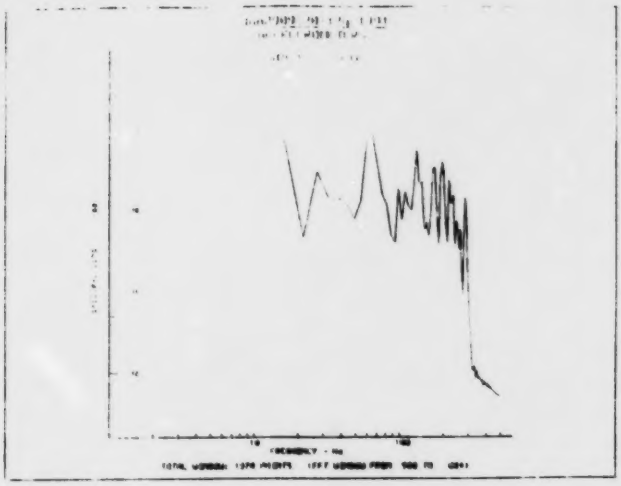
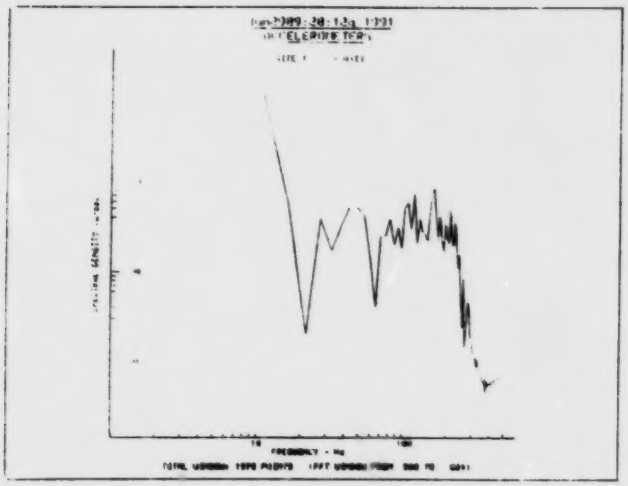


Figure 9 - S-wave spectral density for the event on June 18 at 22:54, east-west, north-south and z orientations.





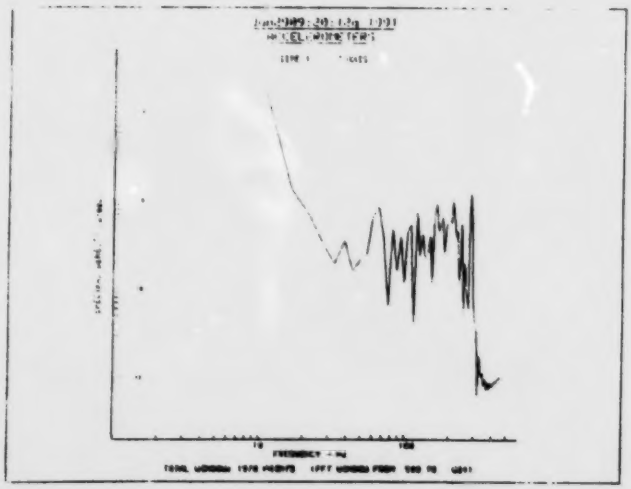


Figure 10 - S-wave spectral density for the event on June 29 at 09:20, east-west, north-south and z orientations.

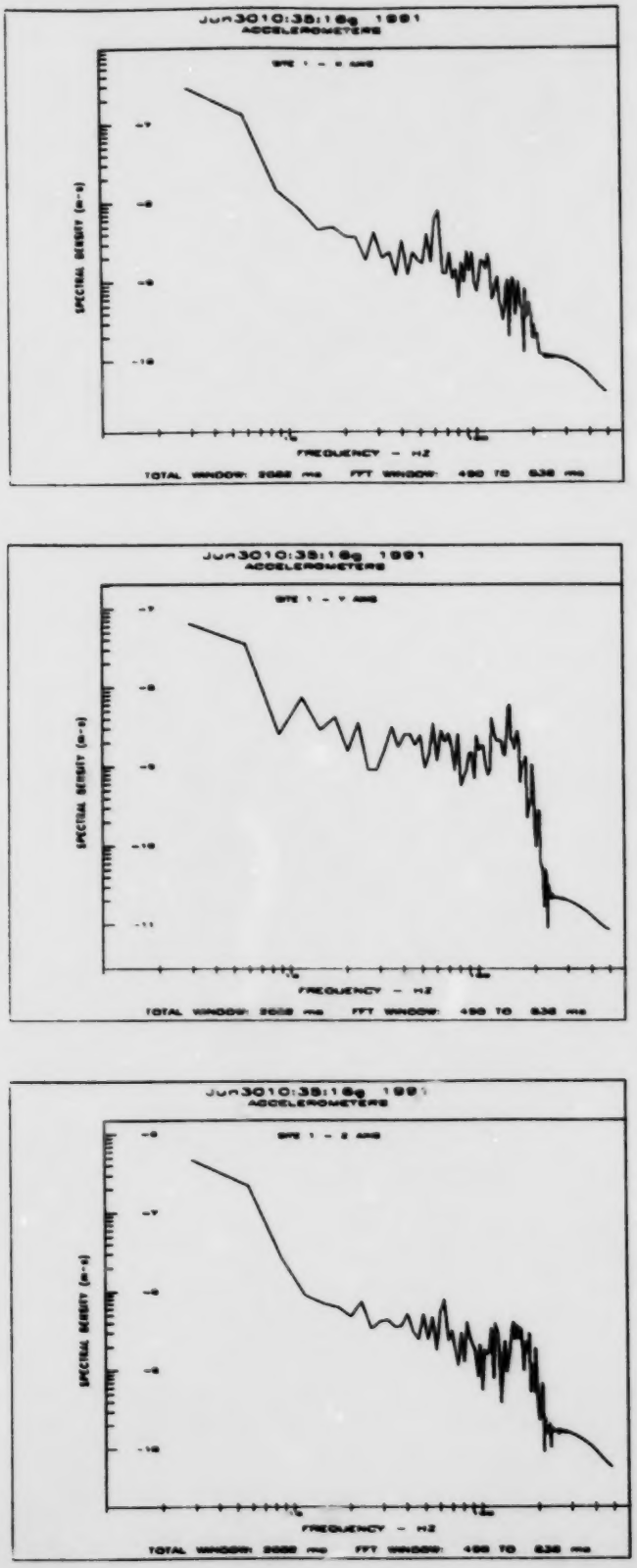
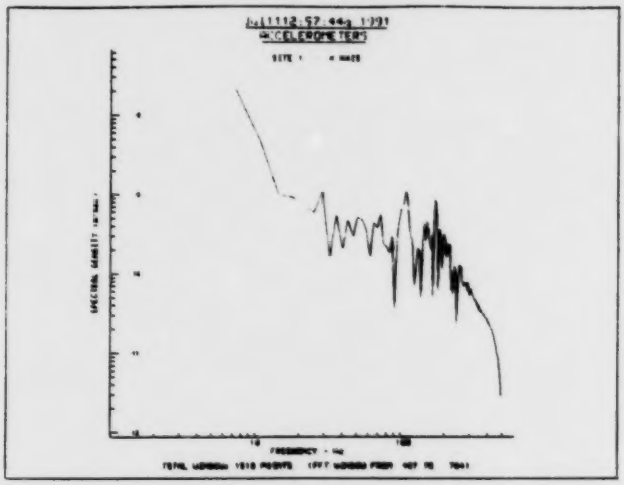
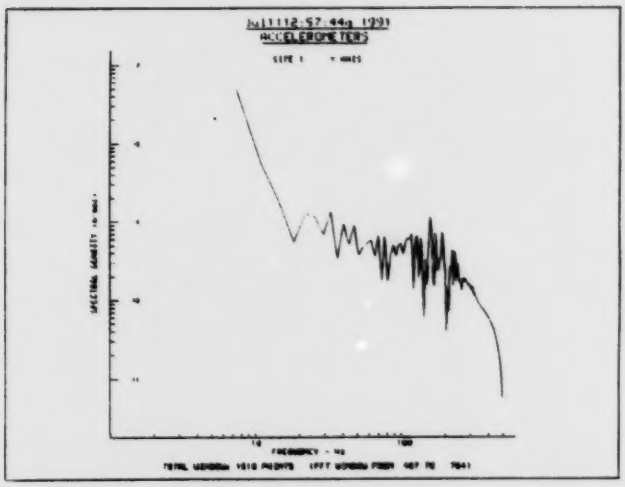


Figure 11 - S-wave spectral density for the event on June 30 at 10:35, east-west, north-south and z orientations.





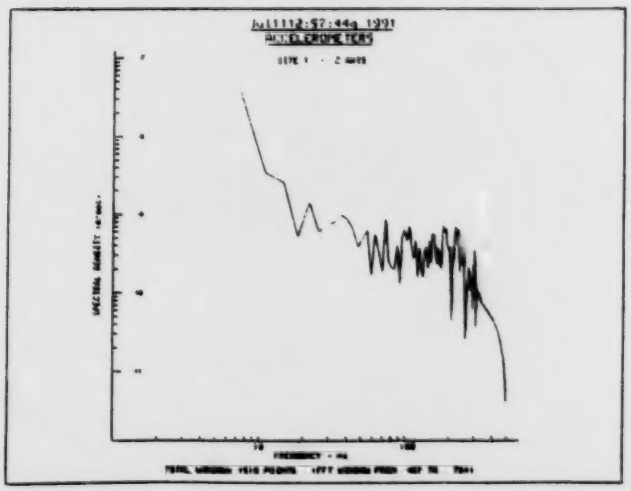
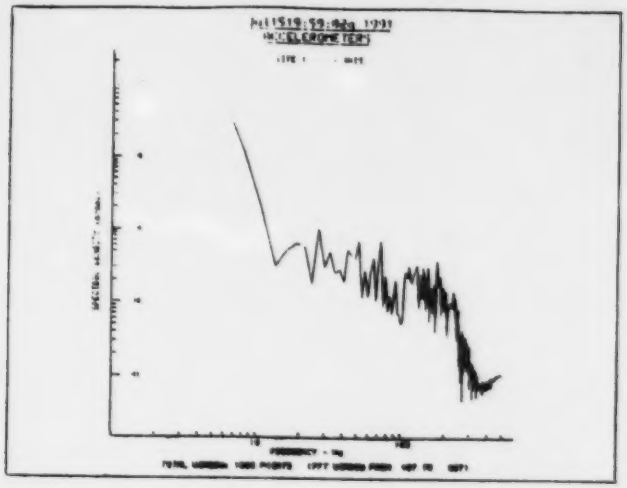
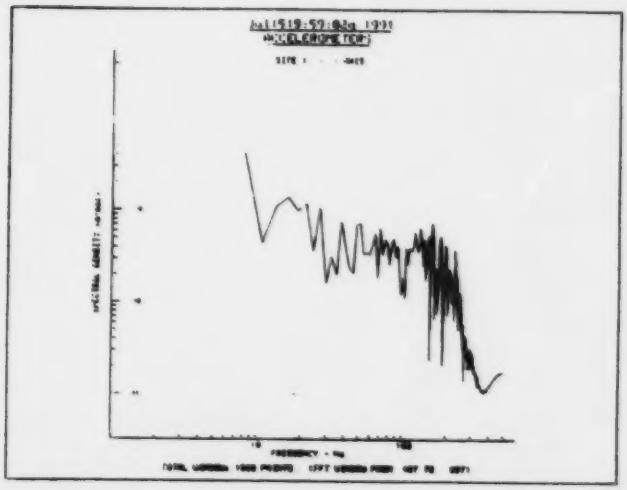


Figure 12 - S-wave spectral density for the event on July 11 at 12:57, east-west, north-south and z orientations.





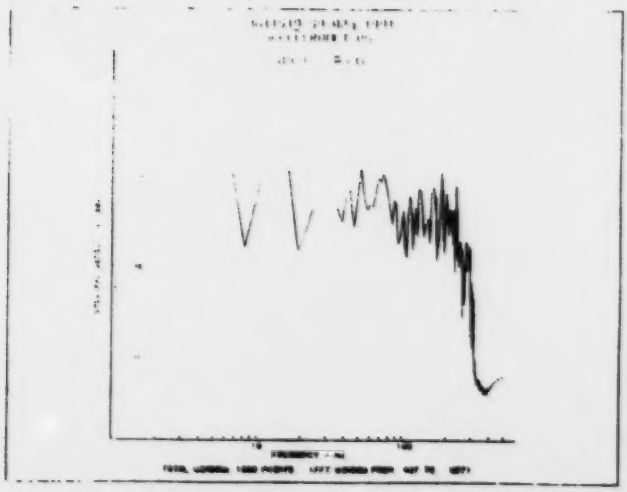
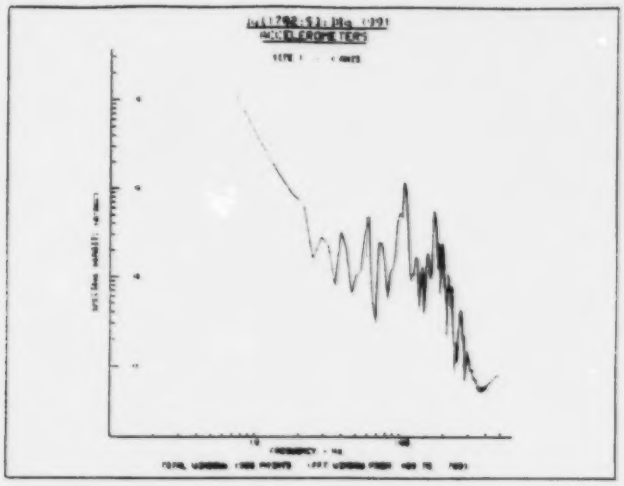
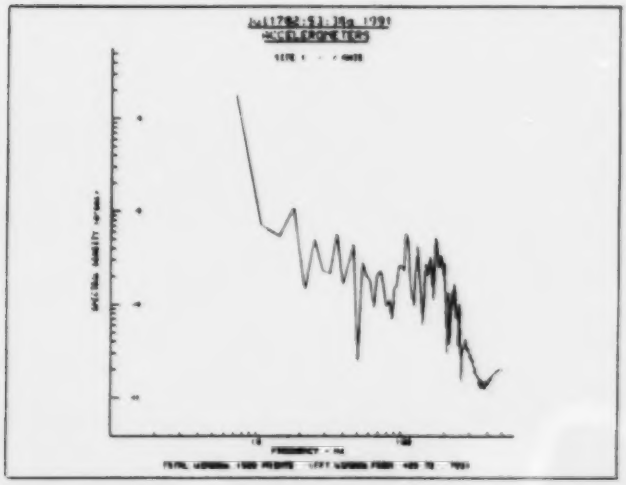


Figure 13 - S-wave spectral density for the event on July 15 at 19:59, east-west, north-south and z orientations.





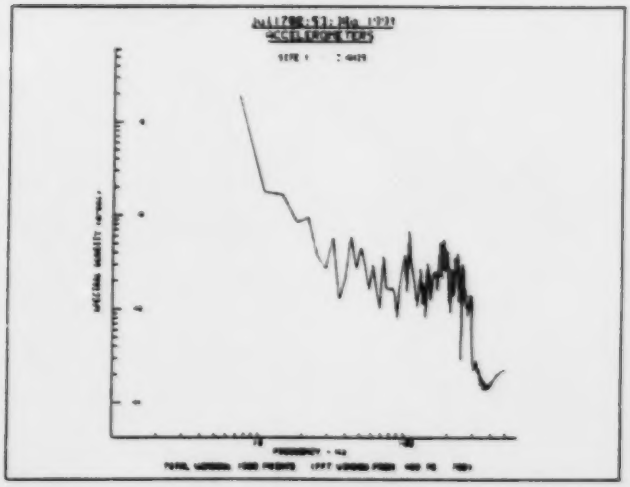


Figure 14 - S-wave spectral density for the event on July 17 at 02:53, east-west, north-south and z orientations.

and the sampling rate, which are interdependent, are too low and make the system impractical for most underground applications.

7. Conclusion

The following major points could be formulated from the full waveform time domain analysis:

- For the seismic events source location, two algorithms were used and the results agree within a few meters.

- The June 27 rockburst event was located at a distance of 441 meters from the PDAS. The quadrant determination has not been established. Even though an attempt at calibration was done with a few blasts, the source mechanism of the seismic events being different from blasts, i.e., dilatation-compression versus shear, no conclusion could be reached.

- The source mechanism producing seismic event at Kidd Creek has a greater shearing than compression-dilatation component. This phenomenon agrees with the fact that heavy shearing is a geological feature of the mine.

- Rockburst magnitudes have been estimated at between -0.5 and 2.5 Mn based on the full waveform energy content.

The principal results of the attempt at full waveform frequency domain analysis are:

- The PDAS sampling frequency and its hardware filter were too low to conduct an underground survey. Since the source-receiver distances were relatively small, i.e., below 1 km, the attenuation in the frequency domain occurs at high frequency. Thereafter the corner frequency was in many cases higher than the 200 Hz filter cut-off frequency and no seismic source parameters could be defined.

- A frequency domain analysis at Kidd Creek would require that the PDAS be placed on surface, far from rockburst activity. The geophone should be placed on an outcrop located approximately 2 km from mining activities and should record data for at least three months.

8. Acknowledgements

The author wishes to thank Dr. T. Yu of Kidd Creek Mine for his co-operation in conducting the survey, and Mr. N. Disley, also of Kidd Creek Mine, for his help in prompt dispatch of diskettes from the PDAS. Thanks are also due to Messrs. M. Plouffe and P. Rochon of CANMET for their advice and numerous discussions. The report also benefitted greatly by critical reviews by Drs. P. Mottahed and B. Arjang.

9. References

Active Filter Products; Design and selection guide, 245 p. Published by Frequency Device Inc., Massachusetts, 1986.

Arjang, B.; Field stresses at the Kidd Creek Mine, Timmins, Division Report MRL 87-142 (TR), CANMET, Energy, Mines and Resources Canada, 13 p., 1987.

Brigham, E.O.; The Fast Fourier Transform. Prentice-Hall, Inc., Englewood Cliffs, New Jersey. 252 pages, 1974.

Brune, J.N.; Tectonic stress and spectra of seismic shear waves from earthquakes, J. Geophys. Res., vol. 75, pp. 4997-5009, 1970.

Brune, J.N.; Seismic moment, seismicity and rate of slip along major fault zones. J. Geophys. Res., vol. 73, pp. 777-784, 1968.

Gendzwill, D. and Prugger A.; Algorithms for micro-earthquake locations. Proc. 4th Conf. on Acoustic Emission/Microseismic Activity, Penn. State University, pp. 601-615, 1989.

Hedley, D.G.F.; Rockburst handbook for Ontario hardrock mines. Special Report, SP92-1E, CANMET, Energy, Mines and Resources Canada, 305 p., 1992.

Hedley, D.G.F.; A five-year review of the Canada-Ontario Industry rockburst project, Special Report SP90-4E, CANMET, Energy, Mines and Resources Canada, 39 p., 1991.

Niewiadomski, J.; Source location techniques using P-wave arrivals, Special Report SP86-15E, CANMET, Energy, Mines and Resources Canada, 16 p., 1986.

Nuttli, O.W.; Seismic wave attenuation and magnitude relations for eastern North America. J. Geophys. Res. vol. 78, pp. 876-885, 1973.

Plouffe, M.; A local seismic survey at Creighton Mine, Division Report MRL 90-076(TR), CANMET, Energy, Mines and Resources Canada, 37 p., 1990.

SIAL, Compagnie Internationale de Géophysique Inc.; In-situ seismic velocity measurements in the Kidd Creek Mine, Final Report, 36 p., 1989.

Walker R.R. and Mannard G.W.; Geology of the Kidd Creek Mine - A progress Report. CIM Bull. vol. 67, no.752, p. 41-57, 1974.

Yu, T.R. and Quesnel, W.J.; Applied rock mechanics for blasthole stoping at Kidd Creek Mines, in Geomechanics applications in underground hardrock mining; SME-AIME, p. 93-107, 1984.

Yu, T.R.; Ground control at Kidd Creek Mine. Underground rock engineering, CIM Special vol. 22, p.1-7, 1980.

APPENDIX A

Digitized Mine Plans

Legend

Colour chart for the digitized mine plans:

Quartz porphyry	blue
Copper	red
Massive sulphide	
Andesite-diorite	
Orebody	green
Shaft	blue circle
Mine workings	lines
Backfilled areas	yellow
MP-250 geophones	⌂
Mining induced seismicity locations	red stars

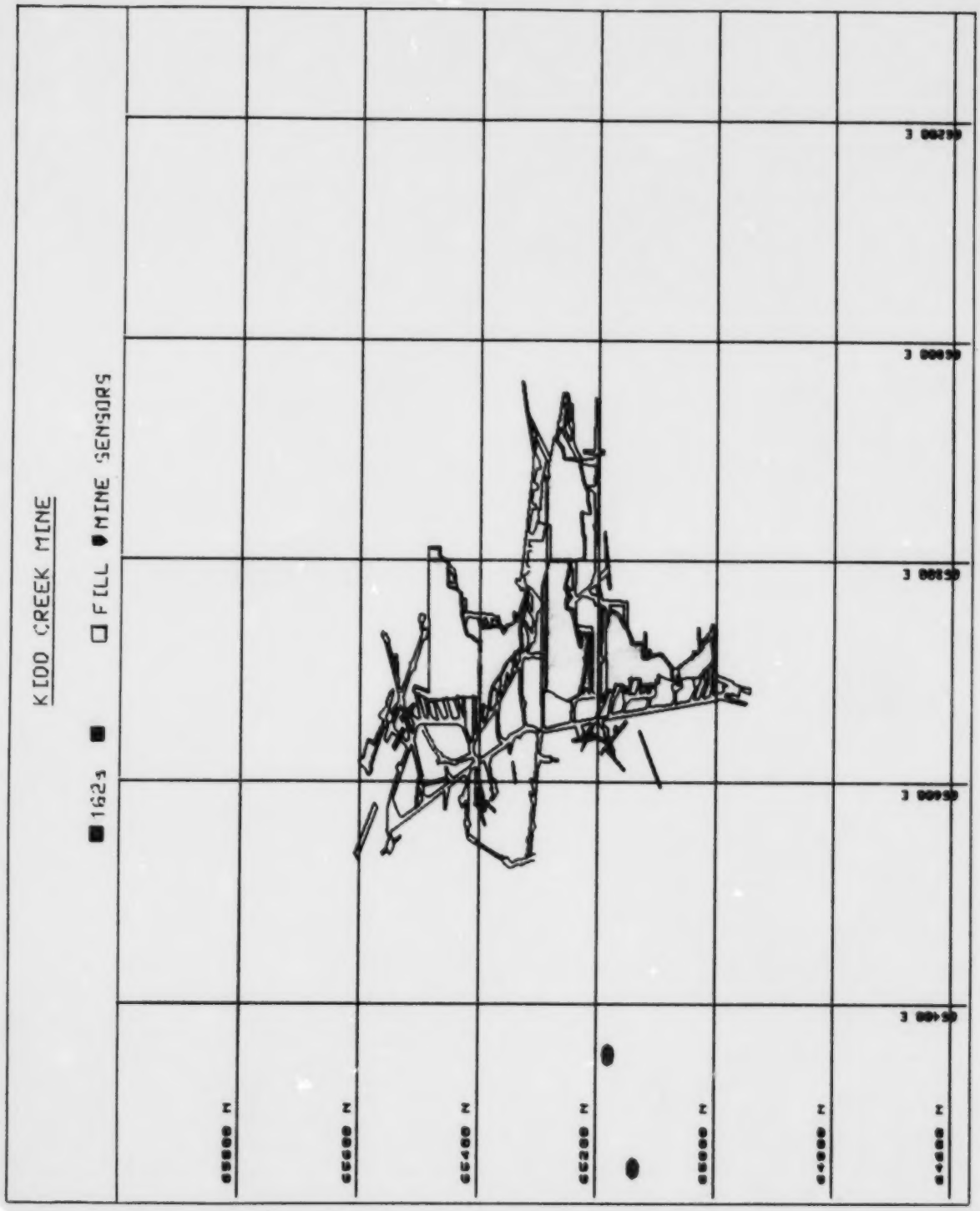


Fig. A-1 - Mine plan: 1623 level.

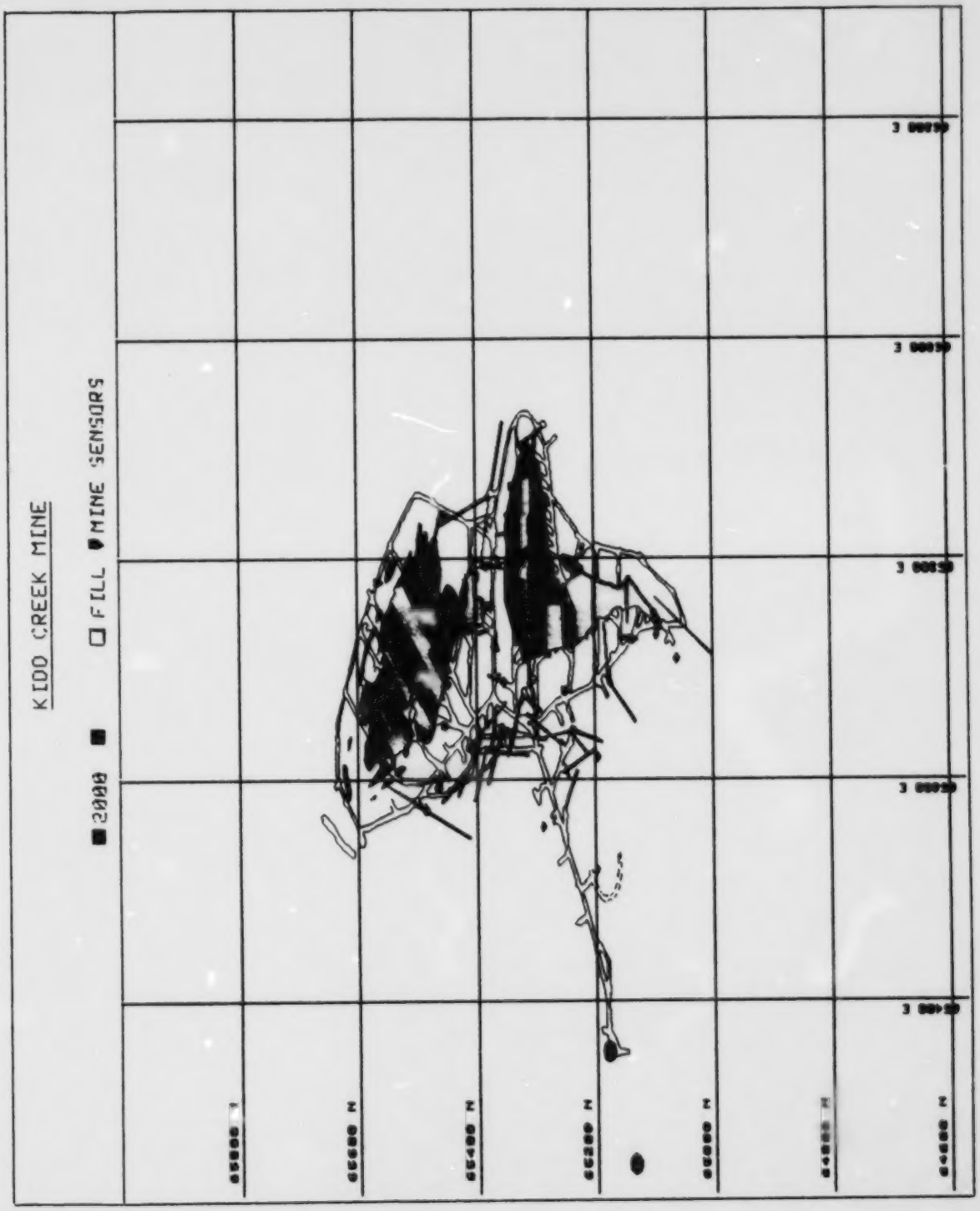


Fig. A-2 - Mine plan: 2000 level.

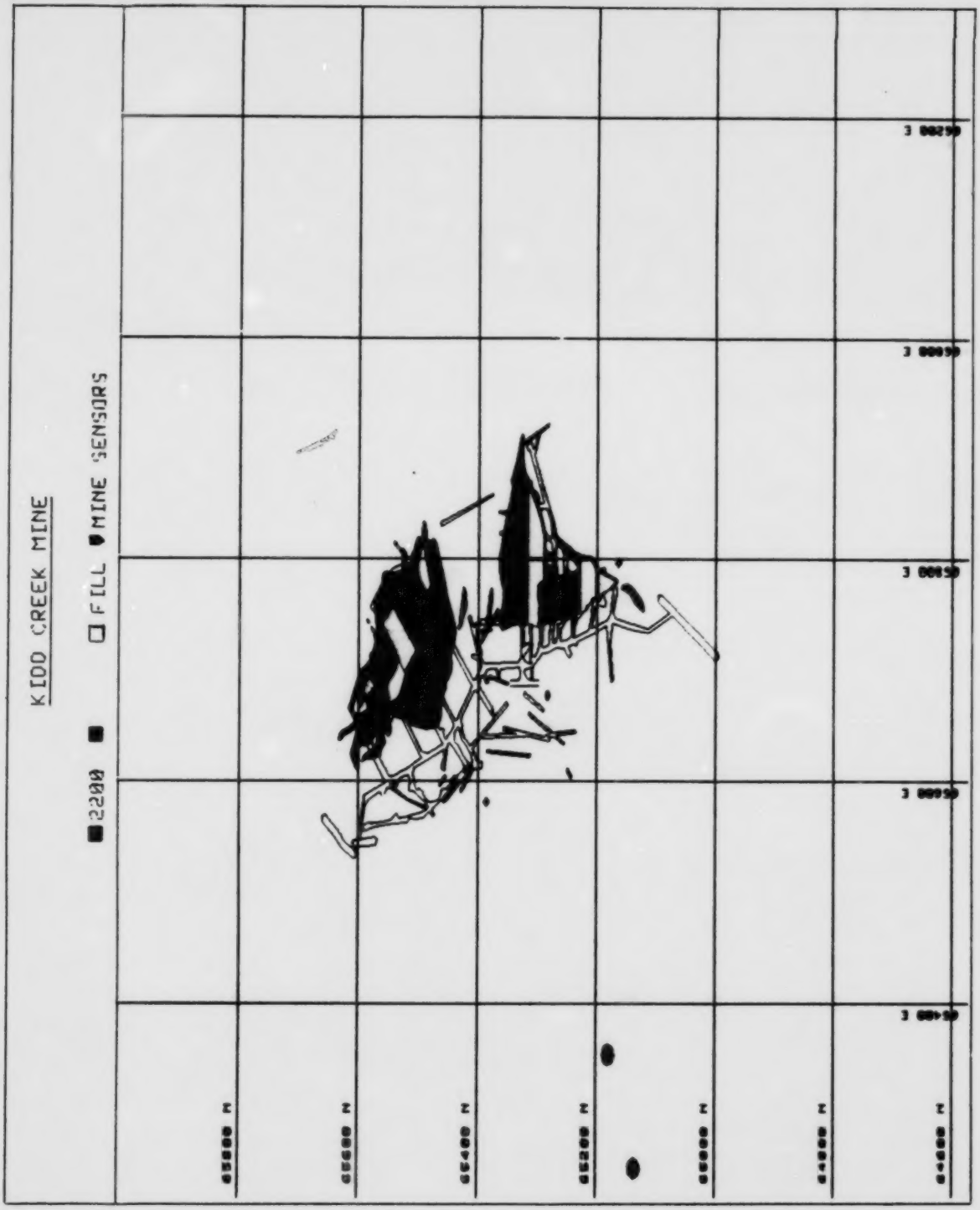


Fig. A-3 - Mine plan: 2200 level.

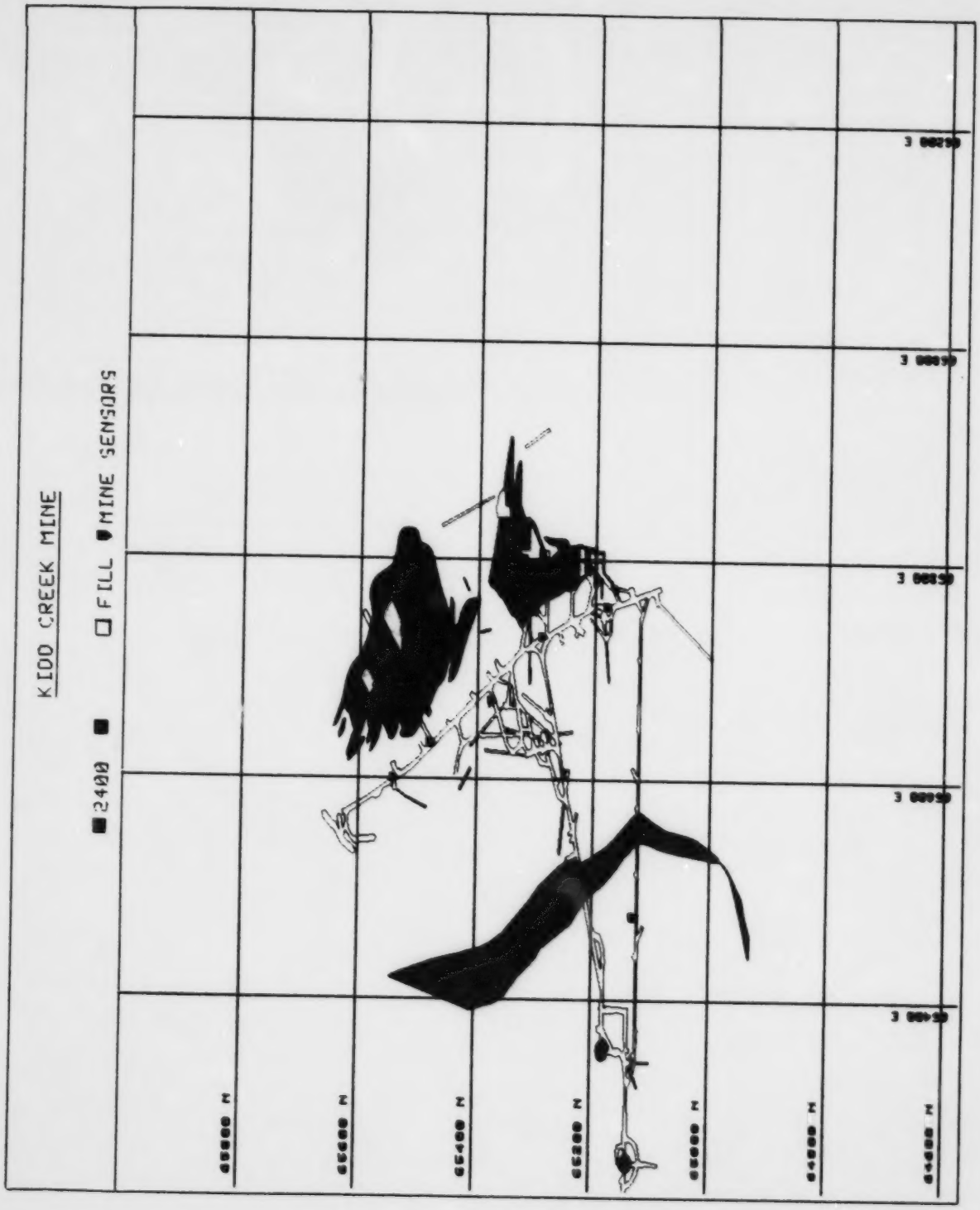


Fig. A-4 - Mine plan: 2400 level.

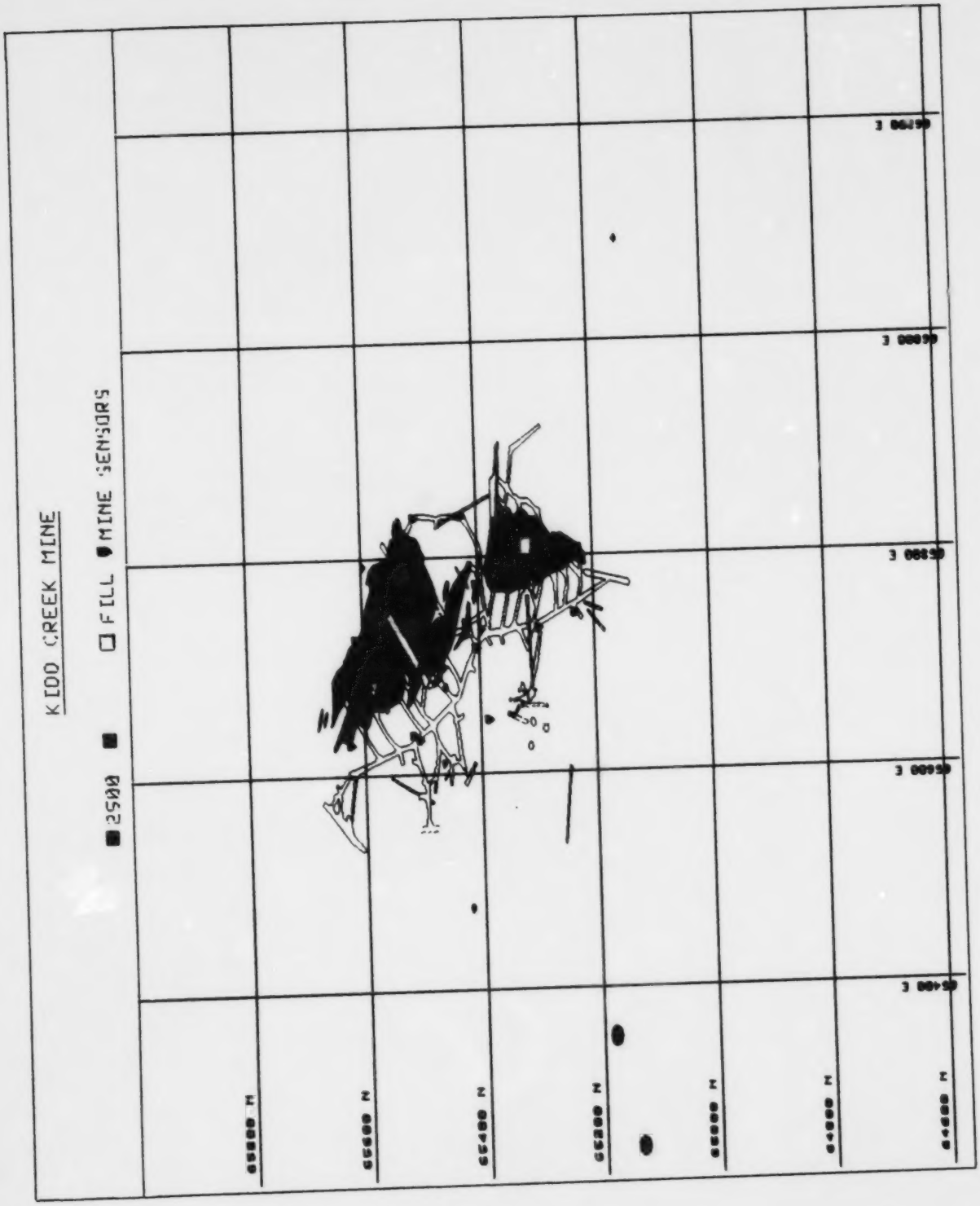


Fig. A-5 - Mine plan; 2500 level.

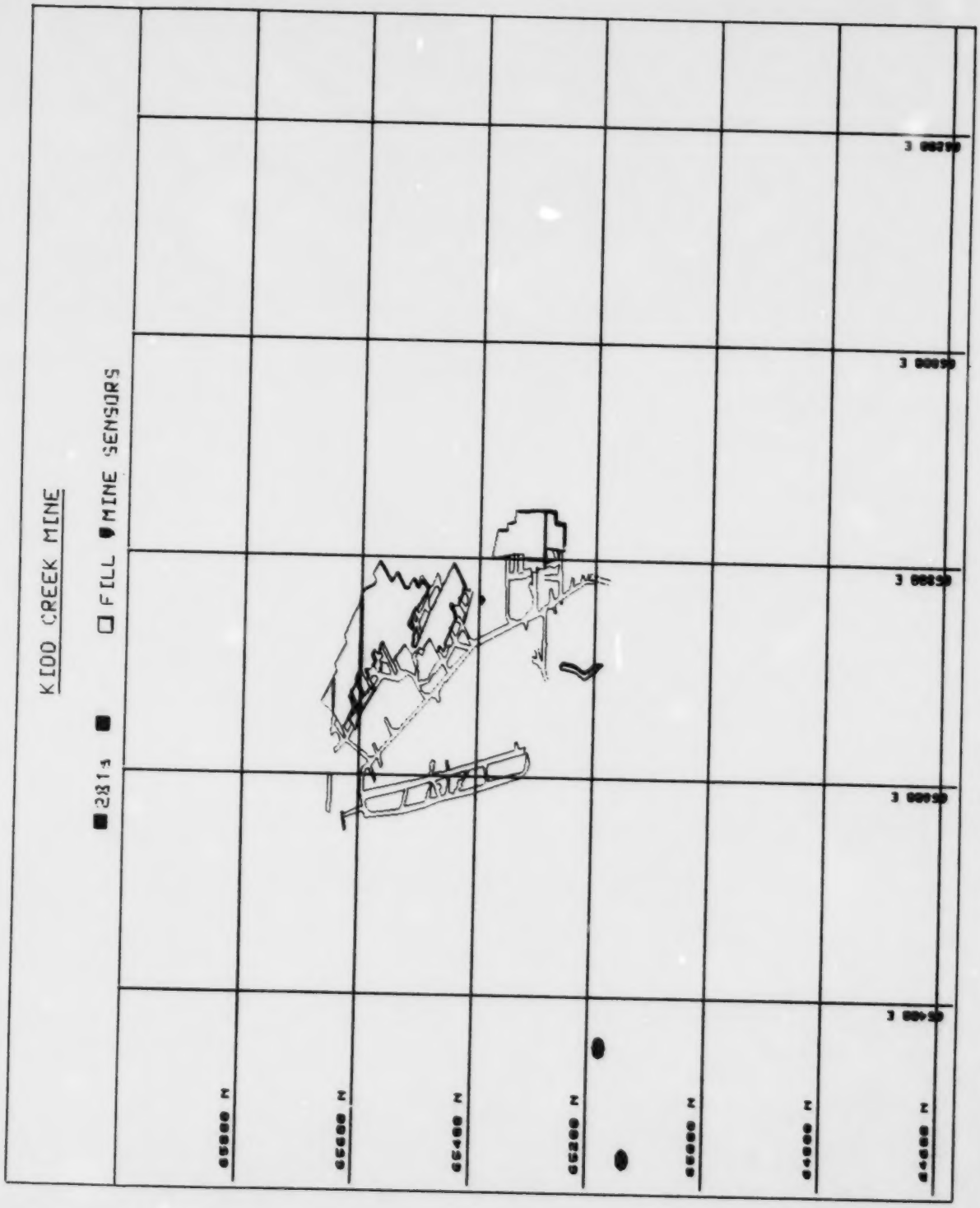


Fig. A-6 - Mine plan; 28ls level.

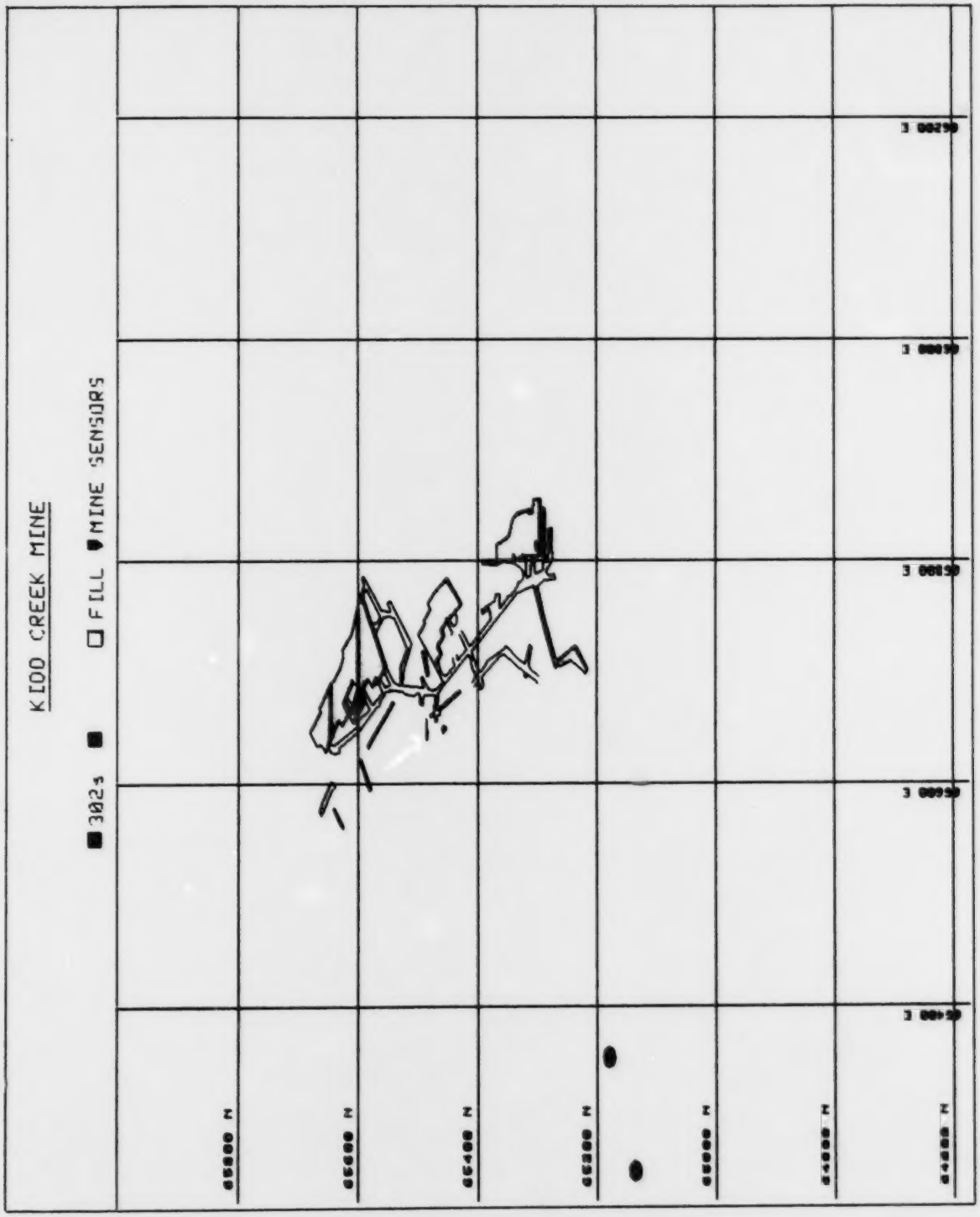


Fig. A-7 - Mine plan; 302s level.

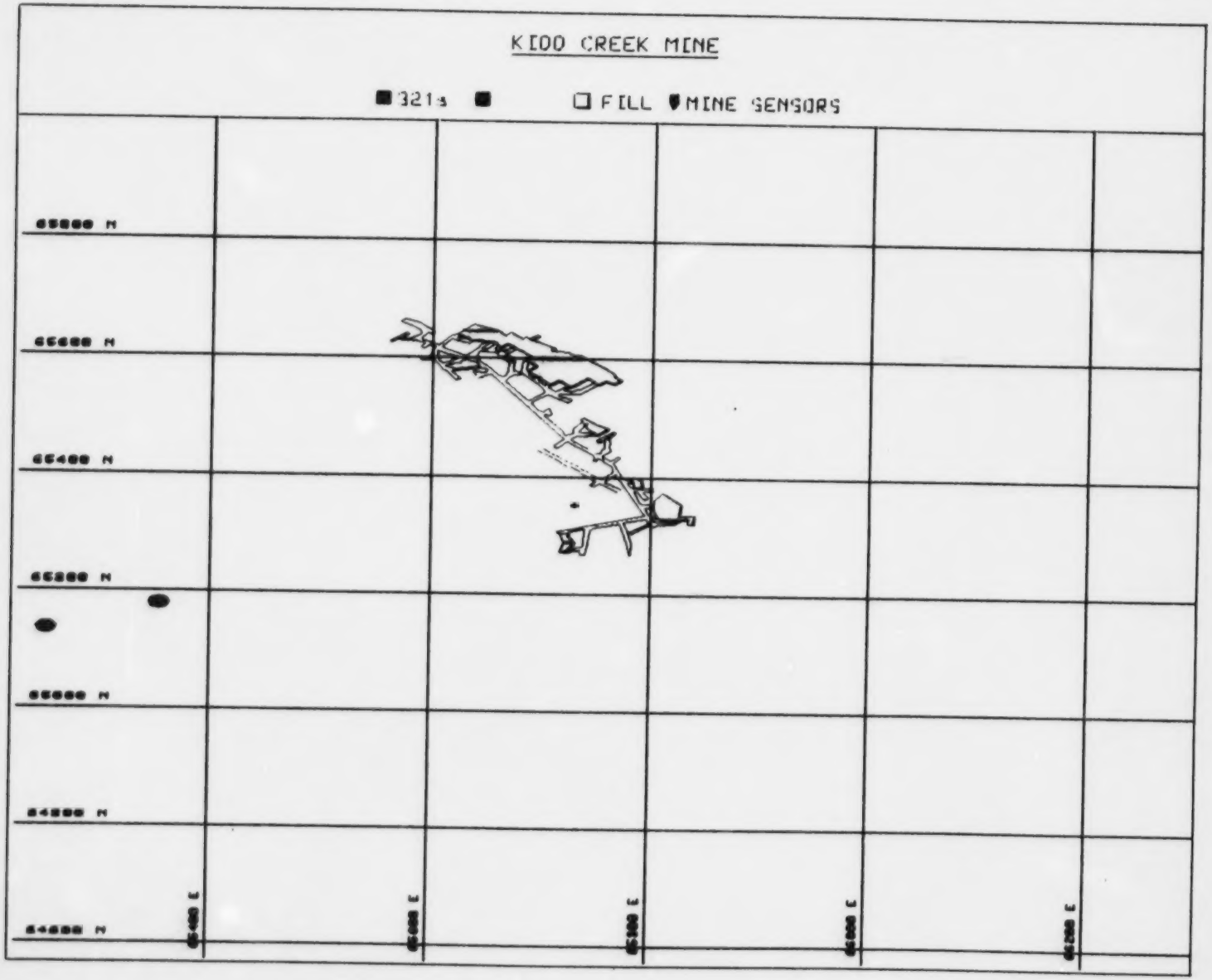


Fig. A-8 - Mine plan; 321s level.

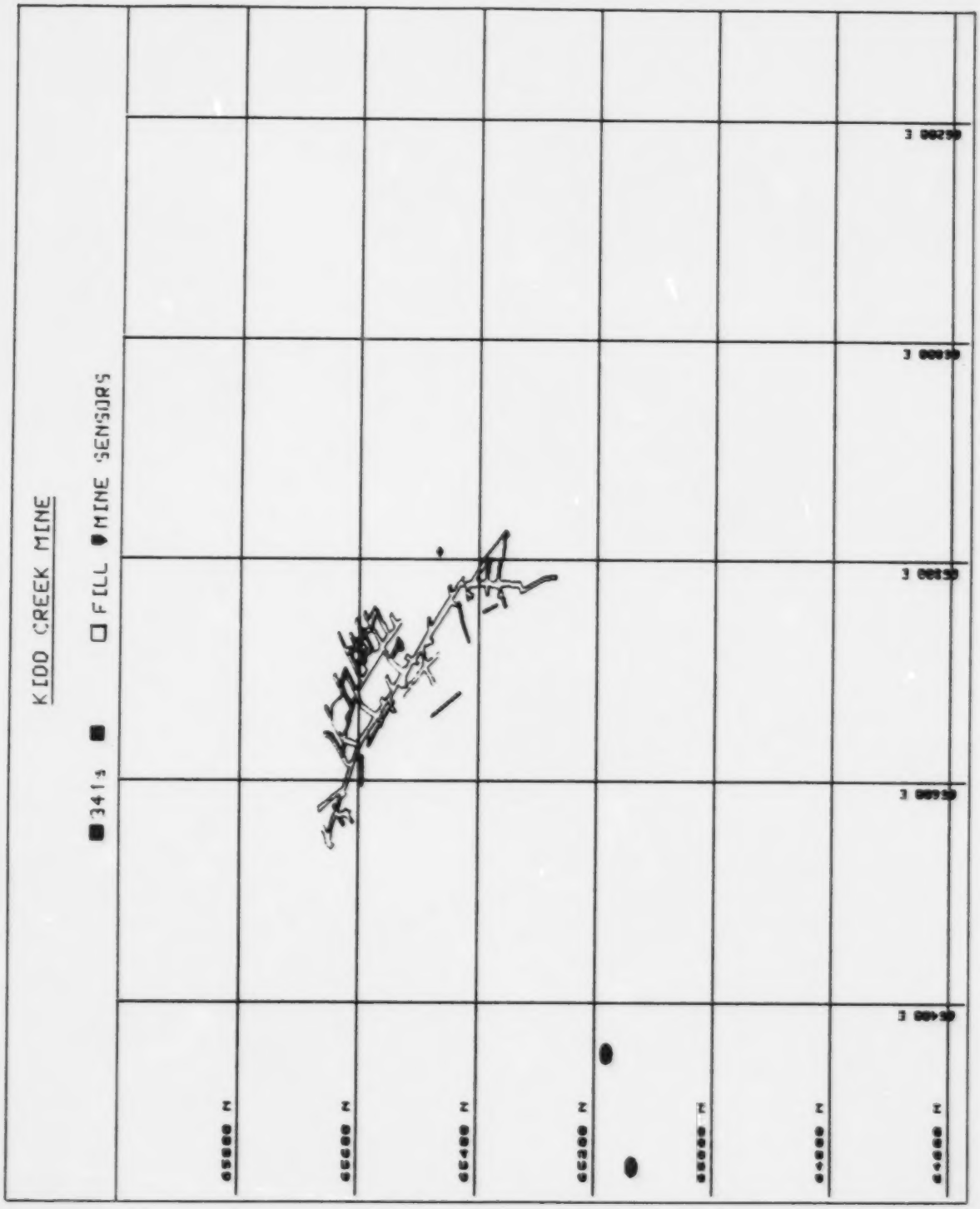


Fig. A-9 - Mine plan; 3413 level.

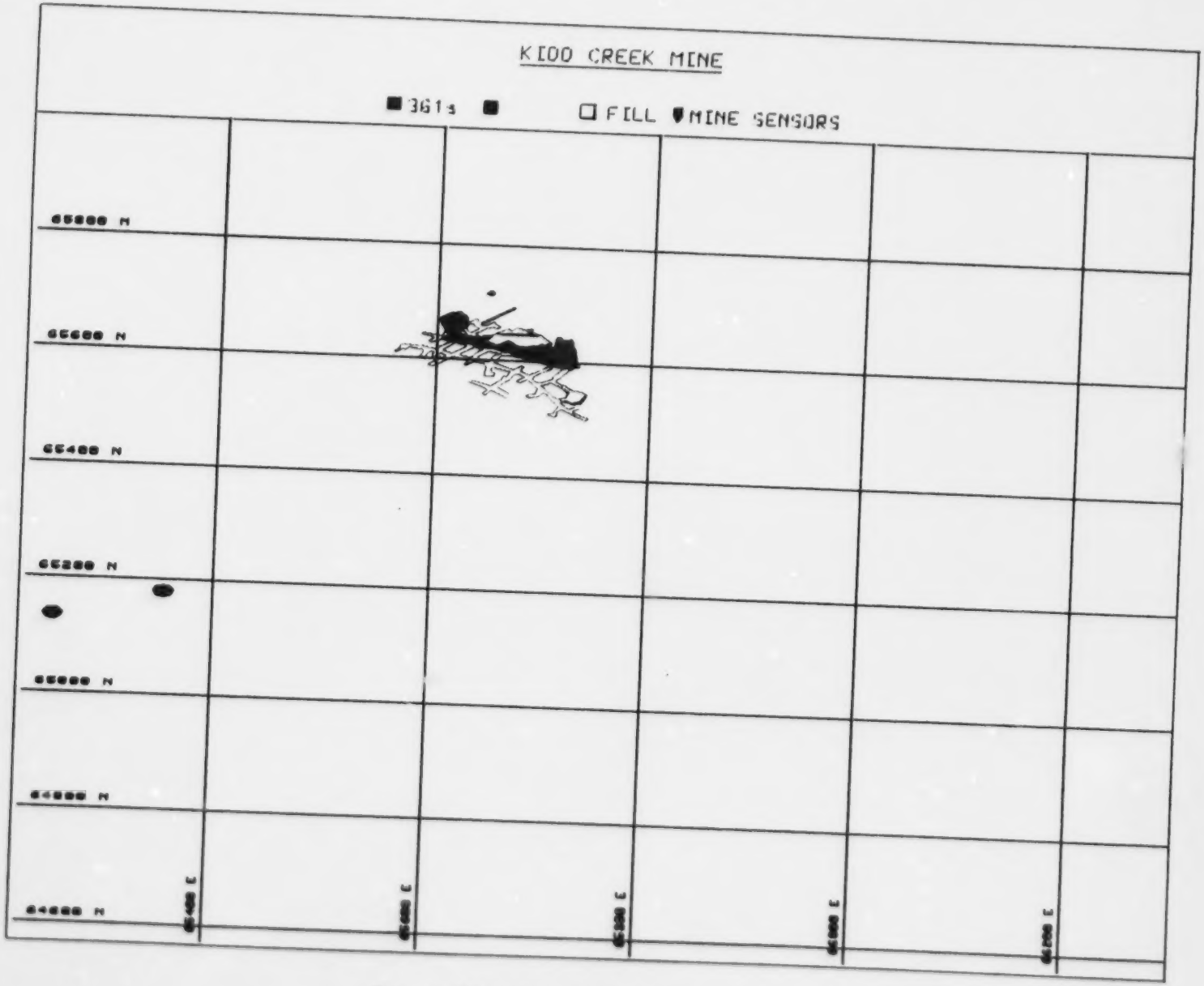


Fig. A-10 - Mine plan; 361s level.

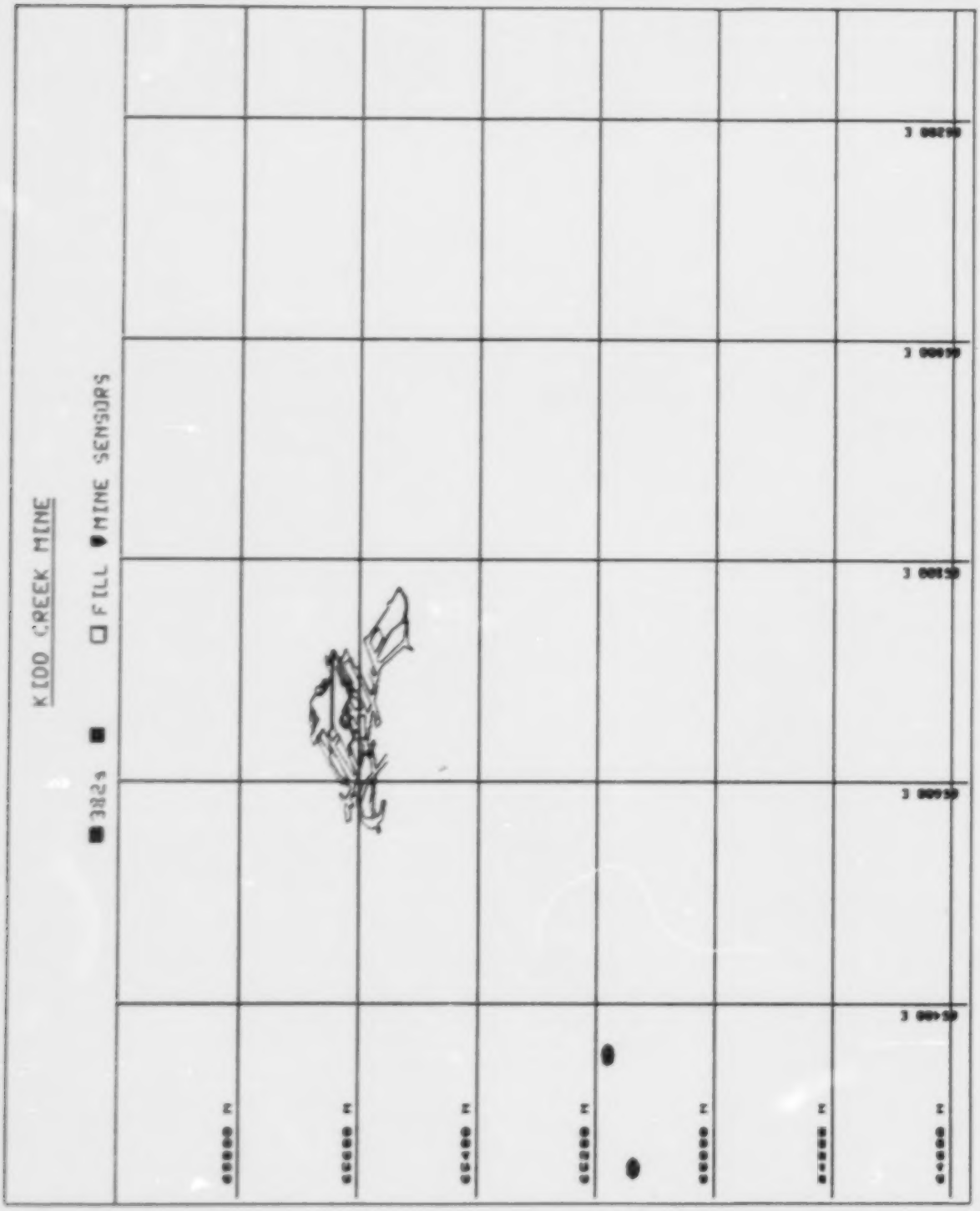


Fig. A-11 - Mine plan; 382s level.

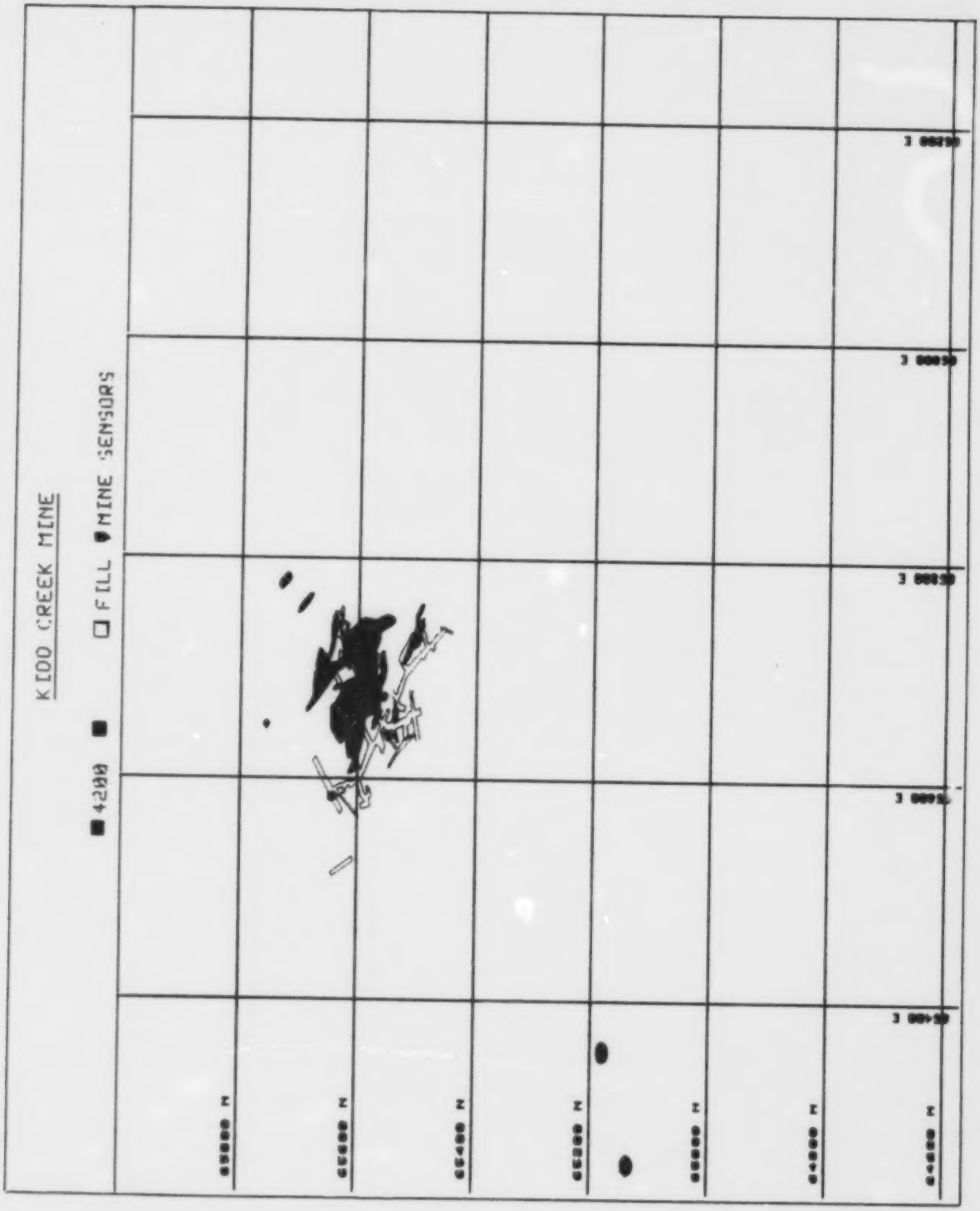


Fig. A-12 - Mine plan; 4200 level.

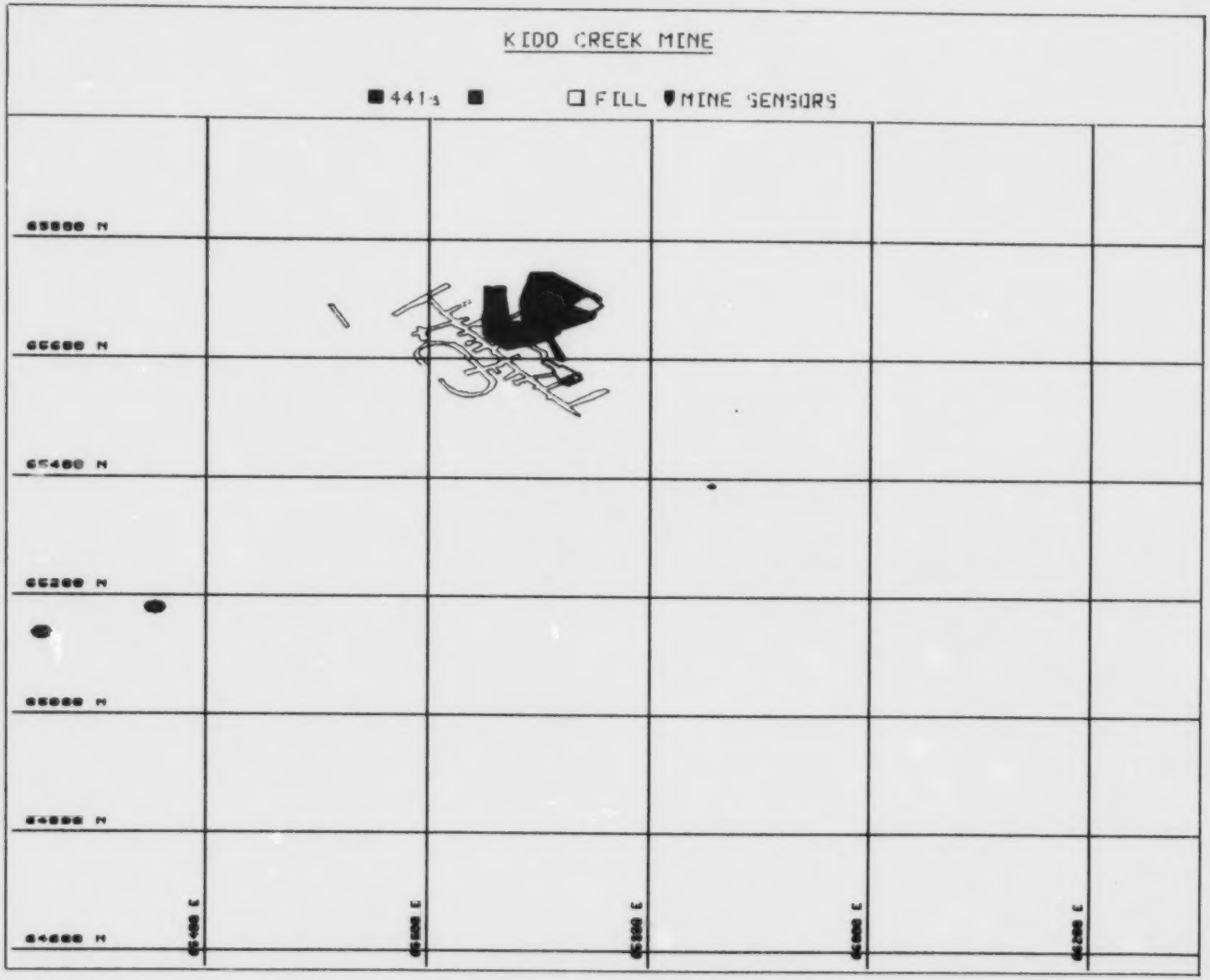


Fig. A-13 - Mine plan; 441s level.

APPENDIX B

Mine Geophone Coordinates

MINE DATA

MINE GEOPHONE COORDINATES

GEOPHONE	EASTING	NORTHING	ELEVATION
1	65818	65444	2844
2	65628	65401	2848
3	65810	65370	2841
4	65692	65314	2848
5	65900	65276	2841
6	65757	65187	2846
7	65656	65198	2848
8	65779	65550	2722
9	65614	65542	2728
10	65840	65438	2720
11	65649	65438	2727
12	65757	65361	2723
13	65865	65321	2723
14	65680	65235	2726
15	65588	65545	2850
16	65727	65120	2727
17	65601	65526	2607
18	65476	65115	2602
19	65633	65464	2606
20	65672	65361	2605
21	65730	65276	2604
22	65758	65165	2605
23	65675	65628	2566
24	65837	65493	2565
25	65632	65490	2563
26	65716	65389	2561
27	65838	65412	2564
28	65747	65218	2562

GEOPHONE	EASTING	NORTHING	ELEVATION
29	65629	65610	2546
30	65726	65597	2542
31	65636	65500	2544
32	65699	65448	2543
33	65650	65371	2542
34	65775	65388	2544
35	65793	65344	2543
36	65734	65281	2543
37	00000	00000	0000
38	00000	00000	0000
39	65608	65615	2272
40	65628	65559	2276
41	65662	65581	2271
42	00000	00000	0000
43	65639	65555	2196
44	65596	65607	2197
45	65706	65559	2197
46	00000	00000	0000
47	65604	65635	2142
48	65655	65530	2146
49	65714	65555	2140
50	65584	65629	2102
51	00000	00000	0000
52	65709	65572	2102
53	65639	65533	2099
54	65624	65658	2038
55	00000	00000	0000
56	00000	00000	0000
57	65692	65559	2038
58	00000	00000	0000
59	65684	65654	1964
60	65724	65555	1964
61	00000	00000	0000
62	00000	00000	0000
63	00000	00000	0000
64	65722	65544	2846

APPENDIX C

Source Location - Block Algorithm

```
   EVENT: EV JD YR TIME      BLOCK INCREMENT   VELOCITY
          1 65 91 11:51          5.     6100.- 3700.
            65596    65427    2675
   BEST FIT AT: X= 65602 Y= 65433 Z= 2684
            65609    65440    2688

        CH 11 CH 33 CH 31 CH 19 CH 12 CH 18 CH
ACTUAL EVENT    0 1955 3055 3200 3555 8385
BLOCK EVENT     0. 1612. 3247. 1371. 3690. 8459.

CHANNELS OUT ARE : 19

"S" WAVE CHANNELS ARE : 31 19 12 18

   ERROR ERS    =   11.4



   EVENT: EV JD YR TIME      BLOCK INCREMENT   VELOCITY
          2 65 91 22:49          5.     6100.- 3700.
            65785    65585    2573
   BEST FIT AT: X= 65794 Y= 65591 Z= 2579
            65798    65598    2586

        CH 23 CH 8 CH 31 CH 25 CH 29 CH 19 CH 26 CH 9
ACTUAL EVENT    0  335  935 1060 1085 1315 1530 1860
BLOCK EVENT     0. 397. 990. 1087. 722. 1337. 1508. 1860.

        CH 17 CH 11 CH 33 CH 12 CH
ACTUAL EVENT  2200 2230 2310 2465
BLOCK EVENT   1316. 2168. 2299. 2436.

CHANNELS OUT ARE : 29 17

   ERROR ERS    =   2.3



   EVENT: EV JD YR TIME      BLOCK INCREMENT   VELOCITY
          1 65 91 11:51          5.     6100.- 3700.
            65773    65635    2713
   BEST FIT AT: X= 65776 Y= 65638 Z= 2722
            65786    65648    2726

        CH 11 CH 33 CH 31 CH 19 CH 12 CH 18 CH
ACTUAL EVENT    0 1955 3055 3200 3555 8385
BLOCK EVENT     0. 1784. 3283. 2962. 3619. 12752.

CHANNELS OUT ARE : 18

"S" WAVE CHANNELS ARE : 31 19 12 18

   ERROR ERS    =   8.1
```

```
   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
         3  66 91  0:52            5.      6100.- 3700.
               65602     65449      2549
   BEST FIT AT:  X= 65611  Y= 65458  Z=  2561
               65615     65462      2562

          CH  31 CH  29 CH  22 CH  18 CH  16 CH
ACTUAL EVENT      0   2125   8455   9075   9470
BLOCK  EVENT      0.  1673.  8091.  9164.  9801.

"S" WAVE CHANNELS ARE :  22 18 16

   ERROR ERS      =    16.6



   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
         3  66 91  0:52            5.      6100.- 3700.
               65578     65493      2631
   BEST FIT AT:  X= 65581  Y= 65505  Z=  2643
               65591     65506      2644

          CH  31 CH  29 CH  22 CH  18 CH  16 CH
ACTUAL EVENT      0   2125   8455   9075   9470
BLOCK  EVENT      0.  2217.  8552.  9114.  9499.

"S" WAVE CHANNELS ARE    29 22 18 16

   ERROR ERS      =     2.6
```

```
   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
           4 123 91 22:36              5.      6100.- 3700.
                 65776    65384     2553
   BEST FIT AT:  X= 65785  Y= 65393  Z=  2562
                 65789    65397     2566

          CH  35 CH  26 CH  32 CH  20 CH  33 CH  36 CH  10 CH  19
ACTUAL EVENT      0   200   825  1150  1280  1345  1895  1900
BLOCK  EVENT      0.  262.  831. 1179. 1395. 1170. 1969. 1972.

          CH  12 CH  21 CH  31 CH  25 CH
ACTUAL EVENT   1905  1985  2180  2325
BLOCK  EVENT   1858. 1357. 2150. 2098.

CHANNELS OUT ARE : 21

   ERROR ERS      =     6.5



   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
           5 123 91 22:37              5.      6100.- 3700.
                 65755    65403     2565
   BEST FIT AT:  X= 65758  Y= 65412  Z=  2574
                 65768    65416     2578

          CH  33 CH  32 CH  31 CH  10 CH  30 CH  13 CH  11 CH  23
ACTUAL EVENT      0   275   330   770  1150  1815  1855  1900
BLOCK  EVENT      0.   82.  549.  813. 1157. 3569. 3161. 1831.

          CH  29 CH   8 CH   1 CH   9 CH
ACTUAL EVENT   1945  2020  2045  2110
BLOCK  EVENT   1936. 3533. 2599. 2095.

CHANNELS OUT ARE : 32 13 11  8  1

"S" WAVE CHANNELS ARE :  32 13 11  8

   ERROR ERS      =     5.8



   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
           6 123 91 23: 7              5.      6100.- 3700.
                 65754    65379     2498
   BEST FIT AT:  X= 65763  Y= 65388  Z=  2504
                 65767    65392     2511

          CH  35 CH  26 CH  32 CH  20 CH  33 CH  36 CH  31 CH  25
ACTUAL EVENT      0    85   470   765  1000  1675  1770  1790
BLOCK  EVENT      0.  129.  492. 1190.  892.  844. 1770. 1806.

          CH  19 CH  12 CH  10 CH  21 CH
ACTUAL EVENT   1810  2545  2865  3180
```

```
BLOCK  EVENT   1900.  2537.  2765.  1438.

CHANNELS OUT ARE : 20 36 21

   ERROR ERS     =    3.9


   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
         7 123 91 23:15            5.      6100.- 3700.
               65723     65337     2358
   BEST FIT AT:  X= 65732  Y= 65346  Z=  2367
               65736     65350     2371

         CH  35 CH  33 CH  32 CH  40 CH  26 CH  20 CH  36 CH  31
ACTUAL EVENT      0    45   140   975   980  1065  1195  1210
BLOCK  EVENT      0.  141.  325. 1109.  214.  977. 2017. 1102.

         CH  25 CH  41 CH  19 CH  21 CH
ACTUAL EVENT   1265  1380  1705  1730
BLOCK  EVENT   1257. 1263. 1607.  997.

CHANNELS OUT ARE : 26 36 21

"S" WAVE CHANNELS ARE :  36

   ERROR ERS     =    6.9


   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
         7 123 91 23:15            5.      6100.- 3700.
               65725     65338     2359
   BEST FIT AT:  X= 65731  Y= 65344  Z=  2365
               65738     65351     2372

         CH  35 CH  33 CH  32 CH  40 CH  26 CH  20 CH  36 CH  31
ACTUAL EVENT      0    45   140   975   980  1065  1195  1210
BLOCK  EVENT      0.  132.  330. 1082.  216.  971.    6. 1102.

         CH  25 CH  41 CH  19 CH  21 CH
ACTUAL EVENT   1265  1380  1705  1730
BLOCK  EVENT   1257. 1240. 1607.  984.

CHANNELS OUT ARE : 26 36 21

   ERROR ERS     =    7.0


   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
         4 123 91 22:36            5.      6100.- 3700.
               65779     65386     2555
   BEST FIT AT:  X= 65785  Y= 65392  Z=  2564
```

```
              65792    65399     2568

         CH  35 CH  26 CH  32 CH  20 CH  33 CH  36 CH  10 CH  19
ACTUAL EVENT     0   200   825  1150  1280  1345  1895  1900
BLOCK  EVENT     0.  264.  845. 1166. 1400. 1163. 1931. 1973.

         CH  12 CH  21 CH  31 CH  25 CH
ACTUAL EVENT   1905  1985  2180  2325
BLOCK  EVENT   1826. 1336. 2166. 2110.

CHANNELS OUT ARE : 21

   ERROR ERS     =    6.4


   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
         5 123 91 22:37            5.      6100.- 3700.
              65780    65460     2594
   BEST FIT AT:  X= 65786  Y= 65466  Z=  2600
              65793    65473     2607

         CH  32 CH  31 CH  10 CH  30 CH  13 CH  11 CH  23 CH  29
ACTUAL EVENT     0    55   495   875  1540  1580  1625  1670
BLOCK  EVENT     0.  962.  469.  807. 1634. 1375. 1546. 1881.

         CH   8 CH   1 CH   9 CH
ACTUAL EVENT   1745  1770  1835
BLOCK  EVENT   709. 2329. 2007.

CHANNELS OUT ARE : 31  8  1

   ERROR ERS     =    8.5


   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
         6 123 91 23: 7            5.      6100.- 3700.
              65754    65379     2498
   BEST FIT AT:  X= 65763  Y= 65388  Z=  2501
              65767    65392     2511

         CH  35 CH  26 CH  32 CH  20 CH  33 CH  36 CH  31 CH  25
ACTUAL EVENT     0   85   470   765  1000  1675  1770  1790
BLOCK  EVENT     0.  138.  490. 1196.  878.  832. 1752. 1793.

         CH  19 CH  12 CH  10 CH  21 CH
ACTUAL EVENT   1810  2545  2865  3180
BLOCK  EVENT   1898. 2556. 2766. 1441.

CHANNELS OUT ARE : 20 36 21

   ERROR ERS     =    4.1
```

```
   EVENT:  EV  JD YR  TIME        BLOCK INCREMENT   VELOCITY
           7 123 91 23:15              5.      6100.- 3700.
                  65723     65335     2360
   BEST FIT AT:  X= 65732  Y= 65344  Z=  2366
                  65736     65348     2373

          CH  35 CH  33 CH  32 CH  40 CH  26 CH  20 CH  36 CH  31
ACTUAL EVENT      0    45   140   975   980  1065  1195  1210
BLOCK  EVENT      0.  145.  353. 1127.  222.  980.   11. 1118.

          CH  25 CH  41 CH  19 CH  21 CH
ACTUAL EVENT   1265  1380  1705  1730
BLOCK  EVENT   1272. 1271. 1620.  989.

CHANNELS OUT ARE : 26 36 21

   ERROR ERS     =     7.3
```

```
   EVENT:  EV  JD YR  TIME        BLOCK INCREMENT   VELOCITY
         8 141 91 21:54              5.      6100.- 3700.
                65657     65447     2632
   BEST FIT AT:  X= 65666  Y= 65456  Z=  2638
                65670     65460     2645

          CH  19 CH  25 CH  31 CH  26 CH  33 CH  32 CH  20 CH   9
ACTUAL EVENT      0   480   935  1075  1335  2175  2850  2980
BLOCK  EVENT      0.  696.  1006.  1098.  1353.  1962.  1958.  2881.

          CH  17 CH  10 CH  11 CH   8 CH
ACTUAL EVENT   3630  4365  4370  4600
BLOCK  EVENT   1949.  4457.  1732.  3811.

CHANNELS OUT ARE : 20 17 11  8

"S" WAVE CHANNELS ARE :  32 20  9 17 10 11  8

   ERROR ERS     =     6.3


   EVENT:  EV  JD YR  TIME        BLOCK INCREMENT   VELOCITY
         9 141 91 21:54              5.      6100.- 3700.
                65471     65406     2550
   BEST FIT AT:  X= 65477  Y= 65415  Z=  2556
                65484     65419     2563

          CH  32 CH   9 CH  29 CH  35 CH   8 CH  10 CH  20 CH  31
ACTUAL EVENT      0   410   965   990  2560  2680  2945  2965
BLOCK  EVENT      0.  477.  371.  1628.  2382.  2855.  1941.  1198.

          CH  36 CH  18 CH  14 CH   1 CH
ACTUAL EVENT   4110  4495  5040  5440
BLOCK  EVENT   4156.  4517.  4968.  8403.

CHANNELS OUT ARE : 29 35 20 31  1

"S" WAVE CHANNELS ARE :  20 31 36 18 14  1

   ERROR ERS     =     6.6
```

```
EVENT:  EV  JD YR  TIME        BLOCK INCREMENT   VELOCITY
        10 143 91 20:31              5.      6100.- 3700.
                  65643    65157     2871
BEST PIT AT:  X= 65649  Y= 65163  Z=  2880
                  65656    65170     2884

          CH   7 CH  29 CH   6 CH   4 CH  14 CH  16 CH   2 CH  18
ACTUAL EVENT      0   485   1185   1665   2080   2205   5900   9100
BLOCK  EVENT      0.  8368.  1112.  1841.  2047.  2116.  5729.  8158.

CHANNELS OUT ARE : 29 18

"S" WAVE CHANNELS ARE :  2 18

   ERROR ERS     =    6.5
```

```
   EVENT: EV JD YR TIME      BLOCK INCREMENT   VELOCITY
        11 144 91 3:55           5.     6100.- 3700.
              65623    65161    2892
   BEST FIT AT: X= 65629 Y= 65170 Z= 2898
              65636    65174    2905

         CH  7 CH  6 CH  4 CH 14 CH 16 CH  2 CH 18 CH 15
ACTUAL EVENT     0  1295  1630  2095  2205  2860  4540  5195
BLOCK  EVENT     0. 1243. 1665. 2090. 2295. 2836. 4498. 5196.

   ERROR ERS    =   2.8


   EVENT: EV JD YR TIME      BLOCK INCREMENT   VELOCITY
        12 144 91 17:55          5.     6100.- 3700.
              65611    65498    2710
   BEST FIT AT: X= 65620 Y= 65507 Z= 2716
              65624    65511    2723

         CH  9 CH 11 CH 19 CH 25 CH  0 CH  8 CH 31 CH 23
ACTUAL EVENT     0   490  1790  1895  1900  2070  2135  2635
BLOCK  EVENT     0.  626. 1333. 1917. 2161. 2088. 2220. 2671.

         CH 29 CH 32 CH 10 CH  4 CH
ACTUAL EVENT  2645  2875  3350  3520
BLOCK  EVENT  2647. 2650. 3166. 3396.

CHANNELS OUT ARE : 19

   ERROR ERS    =   8.5


   EVENT: EV JD YR TIME      BLOCK INCREMENT   VELOCITY
        12 144 91 17:55          5.     6100.- 3700.
              65617    65504    2710
   BEST FIT AT: X= 65626 Y= 65513 Z= 2716
              65630    65517    2723

         CH  9 CH 11 CH 19 CH 25 CH  0 CH  8 CH 31 CH 23
ACTUAL EVENT     0   490  1790  1895  1900  2070  2135  2635
BLOCK  EVENT     0.  748. 1427. 1987. 2147. 2032. 2282. 2650.

         CH 29 CH 32 CH 10 CH  4 CH
ACTUAL EVENT  2645  2875  3350  3520
BLOCK  EVENT  2658. 2707. 3167. 3511.

CHANNELS OUT ARE : 11 19

   ERROR ERS    =   8.0
```

```
EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
        11 144 91  3:55             5.      6100.- 3700.
                65623     65160     2892
BEST FIT AT:  X= 65629  Y= 65166  Z=  2901
                65636     65173     2905

          CH  7 CH  6 CH  4 CH  14 CH  16 CH  2 CH  18 CH  15
ACTUAL EVENT     0  1295  1630  2095  2205  2860  4540  5195
BLOCK  EVENT     0.  1222.  1690.  2103.  2252.  2842.  4520.  5200.

   ERROR ERS    =    2.5
```

```
   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
        13 149 91 21:54            5.      6100.- 3700.
              65550    65331     3034
   BEST FIT AT:  X= 65559  Y= 65340  Z=  3046
              65563    65344     3047


         CH  2 CH  4 CH 15 CH  7 CH  0 CH 12 CH  9 CH  1
ACTUAL EVENT     0   260   940  4300  5455  6640  6700  7520
BLOCK  EVENT     0.  354. 1094. 3508. 5310. 6675. 6710. 5732.

         CH 20 CH 19 CH 11 CH  8 CH
ACTUAL EVENT  7905        9010  8280
BLOCK  EVENT  8737. 893    62. 8430.

CHANNELS OUT ARE :  7    19 11

"S" WAVE CHANNELS ARE :  7  0 12  9  1 20 19 11  8

   ERROR ERS     =    5.5


   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
        15 149 91 21:54            5.      6100.- 3700.
              65835    65529     2892
   BEST FIT AT:  X= 65841  Y= 65538  Z=  2901
              65848    65542     2905

         CH  1 CH  0 CH  3 CH 10 CH 13 CH  5 CH 30 CH  9
ACTUAL EVENT     0   370   535  1535  1885  2775  3490  4140
BLOCK  EVENT     0.  310. 1127. 1549. 2777. 2670. 4414. 2838.

         CH 23 CH 32 CH 31 CH 29 CH
ACTUAL EVENT  4265  4935  6115  6335
BLOCK  EVENT  4463. 4643. 4936. 5039.

CHANNELS OUT ARE :  3 13 30  9 31 29

   ERROR ERS     =    10.2


   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
        14 149 91 21:54            5.      6100.- 3700.
              65618    65619     2638
   BEST FIT AT:  X= 65630  Y= 65625  Z=  2647
              65631    65632     2651

         CH 30 CH  1 CH  0 CH  3 CH 13 CH 10 CH  5 CH 31
ACTUAL EVENT     0   925  3470  3755  4910  5455  5795  7020
BLOCK  EVENT     0. 2983. 3940. 3648. 4044. 5475. 5525. 2003.
```

	CH 4	CH 23	CH 32	CH 14
ACTUAL EVENT	7410	8045	8555	8670
BLOCK EVENT	7770.	129.	3476.	8462.

CHANNELS OUT ARE : 1 0 13 31 23 32

"S" WAVE CHANNELS ARE : 0 10 31 4 23 32 14

ERROR ERS = 10.5

```
   EVENT: EV  JD YR  TIME        BLOCK INCREMENT   VELOCITY
        16 163 91 21:43              5.      6100.- 3700.
                65742     65225      2644
   BEST FIT AT: X= 65745  Y= 65231  Z=  2653
                65755     65238      2657

            CH  21 CH  14 CH  12 CH  20 CH  13 CH   6 CH  26 CH  36
ACTUAL EVENT      0   720  3035  3290  3410  4145  4685  4795
BLOCK  EVENT      0.  486. 2886. 3115. 3356. 4242. 3885. 2161.

            CH  11 CH  33 CH   5 CH  35 CH
ACTUAL EVENT   5065  5130  5515  5695
BLOCK  EVENT   5365. 4351. 5579. 3337.

CHANNELS OUT ARE : 26 36 33 35

"S" WAVE CHANNELS ARE :  12 20 13  6 26 36 11 33  5 35

   ERROR ERS     =     7.8
```

```
   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
        22 165 91 11: 4             5.      6100.- 3700.
                65579    65435     2635
   BEST FIT AT:  X= 65582  Y= 65438  Z=  2641
                65592    65448     2648

          CH  25 CH  11 CH  20 CH  31 CH  33 CH   9 CH  32 CH  26
ACTUAL EVENT      0   140   290   355   510   540   915  1115
BLOCK  EVENT      0.   45.  288.  343.  513.  542.  766.  940.

          CH  12 CH   2 CH  29 CH   8 CH
ACTUAL EVENT   1610  1705  1850  2035
BLOCK  EVENT   1669. 1787. 1570. 2203.

   ERROR ERS     =    7.8


   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
        22 165 91 11: 4             5.      6100.- 3700.
                65579    65429     2635
   BEST FIT AT:  X= 65588  Y= 65438  Z=  2641
                65592    65442     2648

          CH  25 CH  11 CH  20 CH  31 CH  33 CH   9 CH  32 CH  26
ACTUAL EVENT      0   140   290   355   510   540   915  1115
BLOCK  EVENT      0.   31.  261.  347.  510.  566.  735.  904.

          CH  12 CH   2 CH  29 CH   8 CH
ACTUAL EVENT   1610  1705  1850  2035
BLOCK  EVENT   1630. 1811. 1593. 2167.

CHANNELS OUT ARE : 26

   ERROR ERS     =    7.2
```

```
   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
        17 168 91 22:26            5.      6100.- 3700.
                65804     65329     2623
   BEST FIT AT:  X= 65813  Y= 65338  Z=  2632
                65817     65342     2636

          CH  35 CH  12 CH  13 CH  21 CH  36 CH  26 CH  20 CH  10
ACTUAL EVENT      0   190   230   430   675   680   825   830
BLOCK  EVENT      0.  293.  242.  261.  664.  642.  885.  729.

          CH  32 CH  33 CH  14 CH   3 CH
ACTUAL EVENT    1505  1515  1570  1860
BLOCK  EVENT    1480. 1601. 1660. 1968.

   ERROR ERS     =    5.3


   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
        17 168 91 22:26            5.      6100.- 3700.
                65804     65323     2629
   BEST FIT AT:  X= 65810  Y= 65332  Z=  2635
                65817     65336     2642

          CH  35 CH  12 CH  13 CH  21 CH  36 CH  26 CH  20 CH  10
ACTUAL EVENT      0   190   230   430   675   680   825   830
BLOCK  EVENT      0.  204.  164.  133.  581.  626.  817.  735.

          CH  32 CH  33 CH  14 CH   3 CH
ACTUAL EVENT    1505  1515  1570  1860
BLOCK  EVENT    1487. 1554. 1503. 1888.

CHANNELS OUT ARE : 21

   ERROR ERS     =    3.5
```

```
   EVENT:  EV  JD YR  TIME        BLOCK INCREMENT   VELOCITY
         18 169 91 21:54              5.      6100.- 3700.
                 65683     65339     2791
   BEST FIT AT:  X= 65689  Y= 65348  Z=  2800
                 65696     65352     2804

          CH  4 CH  15 CH  11 CH  2 CH  0 CH  9 CH  12 CH  7
ACTUAL EVENT      0   220   445   780   905  1195  1350  1615
BLOCK  EVENT      0. 2755. 1044.  575. 2379. 2643.  732. 1672.

          CH  14 CH  10 CH  19 CH  20 CH
ACTUAL EVENT    2010  2275  2415  2620
BLOCK  EVENT    1254. 2201. 2852. 2250.

CHANNELS OUT ARE : 15 11  0  9 12 14

   ERROR ERS     =   16.8
```

```
   EVENT: EV JD YR  TIME       BLOCK INCREMENT   VELOCITY
        19 178 91  3:29              5.      6100.- 3700.
                65686     65448     2623
   BEST FIT AT:  X= 65695  Y= 65454  Z=  2632
                65699     65461     2636

          CH  32 CH  26 CH  20 CH  11 CH  33 CH  12 CH   8 CH   9
ACTUAL EVENT      0    80   195   325   560   975   980   995
BLOCK  EVENT      0.  151.  168.  286.  675.  899. 1095. 1050.

          CH  10 CH  36 CH  21 CH  23 CH
ACTUAL EVENT   1305  1725  2090  2235
BLOCK  EVENT   1329. 1789. 1545. 1605.

CHANNELS OUT ARE : 21 23

   ERROR ERS     =     4.4
```

```
   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
        20 180 91  8:19            5.      6100.- 3700.
                65704     65042     2729
   BEST FIT AT:  X= 65710  Y= 65054  Z=  2732
                65717     65055     2742

          CH  16 CH  22 CH  14 CH   7 CH  21 CH  18 CH  36 CH  20
ACTUAL EVENT      0  1890  1895  2115  3230  3300  3665  4495
BLOCK  EVENT      0. 1755. 1889. 2038. 3093. 3381. 3738. 4362.
          CH  26 CH   6 CH  33 CH   4 CH

ACTUAL EVENT   4975  4980  5050  5865
BLOCK  EVENT   5046. 1853. 5018. 3556.

CHANNELS OUT ARE :  6  4

   ERROR ERS     =     5.7
```

```
   EVENT: EV JD YR  TIME       BLOCK INCREMENT   VELOCITY
        21 181 91  9:34              5.      6100.- 3700.
                65723    65085     2736
   BEST FIT AT: X= 65732  Y= 65088  Z=  2745
                65736    65098     2749

            CH  16 CH  22 CH   7 CH  14 CH   6 CH  21 CH  18 CH   4
ACTUAL EVENT      0  2010  2140  2675  3095  3415  3550  4370
BLOCK  EVENT      0. 2046. 2159. 1968. 1747. 3245. 4220. 3517.

            CH  20 CH  26 CH  33 CH  32 CH
ACTUAL EVENT   4625  5255  5425  6270
BLOCK  EVENT   4517. 5182. 5258. 6181.

CHANNELS OUT ARE : 14  6 18  4

   ERROR ERS     =     6.6
```

```
   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
         32 184 91 12:19              5.      6100.- 3700.
                65678     65435      2772
   BEST FIT AT:  X= 65687  Y= 65441  Z=  2775
                65691     65448      2785

          CH  11 CH  12 CH  32 CH  33 CH  10 CH
ACTUAL EVENT      0   975  2865  2940  3305
BLOCK  EVENT      0.  935. 2805. 3029. 3390.

"S" WAVE CHANNELS ARE :  10

   ERROR ERS      =     3.8


   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
         33 184 91 17:31              5.      6100.- 3700.
                65675     65447      2555
   BEST FIT AT:  X= 65681  Y= 65453  Z=  2561
                65688     65460      2568

          CH  32 CH  26 CH  20 CH  10 CH  35 CH  36 CH  21 CH  12
ACTUAL EVENT      0   645  2695  3470  4145  4390  4430  4795
BLOCK  EVENT      0.  771. 2342. 3269. 3827. 4463. 4673. 5013.

"S" WAVE CHANNELS ARE :  20 35 36 21 12

   ERROR ERS      =     9.8
```

EVENT: EV JD YR TIME BLOCK INCREMENT VELOCITY
34 185 91 20: 6 5. 6100.- 3700.
65675 65271 2040
BEST FIT AT: X= 65678 Y= 65277 Z= 2655
65688 65284 2659

	CH 20	CH 12	CH 32	CH 25	CH 10
ACTUAL EVENT	0	1890	3850	4835	4910
BLOCK EVENT	0.	2013.	3948.	4787.	4812.

"S" WAVE CHANNELS ARE : 12 32 25 10

ERROR ERS = 3.5

```
   EVENT:  EV  JD YR  TIME        BLOCK INCREMENT   VELOCITY
        35 190 91 20:22              5.      6100.- 3700.
                65552    65276      2683
   BEST FIT AT:  X= 65558  Y= 65282  Z=  2689
                65565    65289      2696

          CH  21 CH   4 CH  19 CH  12 CH  14 CH   7 CH  32 CH  25
ACTUAL EVENT      0   195   370   480   665   915   960  1190
BLOCK  EVENT      0.  302.  355.  407.  526.  211. 1152. 1020.

          CH  10 CH  20 CH  35 CH  18 CH
ACTUAL EVENT   1350  1365  2305  2540
BLOCK  EVENT   2161. 1236. 4516. 2404.

CHANNELS OUT ARE :  7 10 35

'S' WAVE CHANNELS ARE :  14 20 35 18

   ERROR ERS     =    6.9
```

```
   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
        36 191 91  8:38            5.      6100.- 3700.
              64755    66380     3317
   BEST FIT AT:  X= 64758  Y= 66392  Z=  3329
              64768    66393     3330

         CH  19 CH  20 CH  33 CH  18 CH  22 CH
ACTUAL EVENT      0  1395  1895  2730  4585
BLOCK  EVENT      0.  1481.  1664.  2776.  4500.

   ERROR ERS     =    8.1



   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
        37 191 91  9:40            5.      6100.- 3700.
              66085    65134     2554
   BEST FIT AT:  X= 66094  Y= 65140  Z=  2563
              66098    65147     2567

         CH   4 CH  11 CH  15 CH  12 CH  14 CH
ACTUAL EVENT      0   640  3005  3150  3715
BLOCK  EVENT      0.   615.  3053.  3152.  3729.

'S' WAVE CHANNELS ARE :  12 14

   ERROR ERS     =    1.7



   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
        38 191 91 11:56            5.      6100.- 3700.
              65871    65287     2689
   BEST FIT AT:  X= 65880  Y= 65293  Z=  2695
              65884    65300     2702

         CH  26 CH  32 CH  19 CH  20 CH  33 CH
ACTUAL EVENT      0   665  1520  2360  4170
BLOCK  EVENT      0.   822.  1325.  2583.  3946.

'S' WAVE CHANNELS ARE :  20 33

   ERROR ERS     =    9.6
```

```
   EVENT:  EV  JD YR  TIME        BLOCK INCREMENT   VELOCITY
        39 192 91 11:58              5.      6100.- 3700.
                65647     65705      2264
   BEST FIT AT:  X= 65650  Y= 65711  Z=  2270
                 65660     65718     2277

            CH  39 CH  41 CH  40 CH  43 CH  59 CH
ACTUAL EVENT      0   1875   2180   3135   6690
BLOCK  EVENT      0.  1810.  2436.  2958.  6744.

"S" WAVE CHANNELS ARE :  41 40 43 59

   ERROR ERS     =     6.0
```

```
EVENT:  EV  JD YR  TIME        BLOCK INCREMENT   VELOCITY
        40 193 91 22:53              5.      6100.- 3700.
                65655     65470     2590
BEST FIT AT:  X= 65661  Y= 65476  Z=  2599
                65668     65483     2603

          CH  19 CH  25 CH  31 CH  32 CH  20 CH  26 CH  33 CH  17
ACTUAL EVENT      0   195   440   815  1230  1260  1295  1455
BLOCK  EVENT      0.  279.  553.  688. 1384. 1286. 1454. 1610.

          CH  11 CH  29 CH   9 CH  23 CH
ACTUAL EVENT   1515  1870  1985  2160
BLOCK  EVENT   1685. 1907. 1985. 2048.

"S" WAVE CHANNELS ARE :  17

   ERROR ERS    =    6.8
```

```
   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
        41 196 91  0:27            5.      6100.- 3700.
                65620    65568     2217
   BEST FIT AT:  X= 65626  Y= 65577  Z=  2223
                65633    65581     2230

          CH  40 CH  41 CH  45 CH  39 CH  26 CH
ACTUAL EVENT      0    10   475   835  5780
BLOCK  EVENT      0.   68.  492.  827.  5592.

"S" WAVE CHANNELS ARE :  39

   ERROR ERS     =     6.0



   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
        42 196 91  1:39            5.      6100.- 3700.
                64735    65124     2614
   BEST FIT AT:  X= 64735  Y= 65130  Z=  2620
                64748    65137     2627

          CH  33 CH  20 CH  36 CH  26 CH  35 CH
ACTUAL EVENT      0   240   965  1965  2335
BLOCK  EVENT      0.  258.  1047.  1097.  2176.

CHANNELS OUT ARE : 26

   ERROR ERS     =     6.3

WARNING: YOU HAVE ONLY  4 GEOPHONES IN YOUR SEQUENCE



   EVENT:  EV  JD YR  TIME       BLOCK INCREMENT   VELOCITY
        43 196 91 18:58            5.      6100.- 3700.
                65579    65385     2892
   BEST FIT AT:  X= 65588  Y= 65391  Z=  2898
                65592    65398     2905

          CH   2 CH   4 CH  15 CH  11 CH   7 CH   9 CH  14 CH  12
ACTUAL EVENT      0  1220  1560  2055  2385  2795  2980  3035
BLOCK  EVENT      0. 1212. 1582. 2012. 2391. 2689. 3032. 2956.

          CH  19 CH  20 CH  25 CH  26 CH
ACTUAL EVENT   3775  4210  4615  4805
BLOCK  EVENT   3927. 3959. 4709. 4847.

   ERROR ERS     =     6.4
```

```
   EVENT:  EV  JD YR  TIME        BLOCK INCREMENT   VELOCITY
        44 197 91 23:35             5.      6100.- 3700.
                65612     65180     2816
   BEST FIT AT:  X= 65621  Y= 65189  Z=  2822
                65625     65193     2829

          CH   7 CH   4 CH  14 CH  16 CH  18 CH
ACTUAL EVENT       0  1875  2390  3670  3760
BLOCK  EVENT       0.  1665.  2560.  3545.  3757.

"S" WAVE CHANNELS ARE :  14 16

   ERROR ERS      =     7.5
```

```
EVENT:  EV  JD YR  TIME        BLOCK INCREMENT   VELOCITY
        45 198 91  1:54              5.      6100.- 3700.
                65573     65373     2680
BEST FIT AT:  X= 65582  Y= 65379  Z=  2686
                65586     65386     2693

            CH   4 CH  15 CH   7 CH   8 CH  14 CH
ACTUAL EVENT      0    525    705    895   1555
BLOCK  EVENT      0.   444.   780.   935.  1448.

"S" WAVE CHANNELS ARE :  14

   ERROR ERS     =     4.1
```

```
   EVENT: EV JD YR TIME       BLOCK INCREMENT   VELOCITY
        46 202 91 8:36              5.      6100.- 3700.
                65686     65473     2648
   BEST FIT AT: X= 65695  Y= 65482  Z=  2651
                65699     65486     2661

            CH  19 CH  17 CH   8 CH  31 CH  25 CH  32 CH  20 CH   9
ACTUAL EVENT      0   590   795   810   815   825   915   935
BLOCK  EVENT      0.  558.  830.  735.  489.  567.  865.  789.

            CH  24 CH  26 CH  33 CH  10 CH
ACTUAL EVENT   1095  1160  1335  1435
BLOCK  EVENT   1437.  859. 1365. 1439.

   ERROR ERS     =   11.8
```

```
   EVENT:  EV  JD YR  TIME        BLOCK INCREMENT   VELOCITY
         27 214 91  0:30              5.       6100.- 3700.
                 65805     65529      2573
   BEST FIT AT:  X=  65814  Y=  65535  Z=  2579
                 65818     65542      2586

            CH   8 CH  23 CH   7 CH   4 CH  16 CH  18 CH
ACTUAL EVENT      0    280   5710   7570   9390   9480
BLOCK  EVENT      0.   324.  5102.  7544.  9712.  6420.

CHANNELS OUT ARE : 18

"S" WAVE CHANNELS ARE :   4 16

   ERROR ERS      =    19.5
```

```
   EVENT:  EV  JD YR  TIME        BLOCK INCREMENT   VELOCITY
           28 228 91 11:12              5.      6100.- 3700.
                65792     65148      2654
   BEST FIT AT:  X= 65798  Y= 65157  Z=  2660
                65805     65161      2667

          CH  22 CH  16 CH  21 CH  36 CH  14 CH   6 CH  13 CH  26
ACTUAL EVENT      0  1815  2640  2670  3195  3865  4030  4265
BLOCK  EVENT      0. 1699. 2879. 3799. 3096. 4089. 3959. 6046.

          CH  18 CH   5 CH  12 CH   7 CH
ACTUAL EVENT   4730  4740  4900  5245
BLOCK  EVENT   7793. 5348. 4753. 5341.

CHANNELS OUT ARE : 36 26 18  5

"S" WAVE CHANNELS ARE :  16 21 36 14  6 13 26 18  5 12  7

   ERROR ERS     =     5.7
```

```
   EVENT: EV JD YR  TIME       BLOCK INCREMENT   VELOCITY
        30 240 91 21:52              5.      6100.- 3700.
                65742     65554     2654
   BEST FIT AT:  X= 65751  Y= 65560  Z=  2660
                65755     65567     2667

          CH  8 CH  24 CH  30 CH  23 CH  9 CH  10 CH  17 CH  19
ACTUAL EVENT      0  1075  1080  1090  1395  1550  1560  1580
BLOCK  EVENT      0.  1243.  941.  1146. 1397.  1537.  1540.  1519.

          CH  25 CH  29 CH  11 CH  31 CH
ACTUAL EVENT    1675   1685   1765   1820
BLOCK  EVENT    1639.  1730.  1702.  1721.

   ERROR ERS     =     4.9
```

```
EVENT:  EV  JD YR  TIME        BLOCK INCREMENT   VELOCITY
        22 247 91 21:57            100.      6100.- 3700.
                65600     65700     1950
BEST FIT AT:  X= 65650  Y= 65750  Z=  2050
                65800     65900     2150

            CH  54 CH  59 CH  57 CH  52 CH  47 CH  49 CH  53 CH  50
ACTUAL EVENT      0   280   370   375  1125  1865  2275  2355
BLOCK  EVENT      0.  606.  1632. 1611.  950.  2094.  2072.  2402.

            CH  60 CH  48 CH  45 CH  43 CH
ACTUAL EVENT   4725  4750  4900  5045
BLOCK  EVENT   4518. 4909. 5108. 5011.

CHANNELS OUT ARE : 57 52

"S" WAVE CHANNELS ARE :  50 60 48 45 43

    ERROR ERS     =    10.6
```

```
   EVENT:  EV  JD YR  TIME        BLOCK INCREMENT   VELOCITY
         23 256 91 22:52            100.       6100.- 3700.
                65550     65350      2350
   BEST FIT AT:  X= 65650  Y= 65450  Z=  2450
                 65750     65550      2550

          CH  30 CH  24 CH  39 CH  15 CH  18 CH  27 CH  23 CH   3
ACTUAL EVENT      0    90   1260   3375   3405   3650   3945   8215
BLOCK  EVENT      0.   563.  934.  3712.  3567.  2926.  2678.  8517.

          CH   5 CH
ACTUAL EVENT    9935
BLOCK  EVENT   10292.

CHANNELS OUT ARE : 24 39 23

"S" WAVE CHANNELS ARE :  27 23  3  5

   ERROR ERS      =    17.5
```

```
   EVENT:  EV  JD YR  TIME        BLOCK INCREMENT   VELOCITY
         24 266 91 21:52              5.      6100.- 3700.
                 65851     65372      2028
   BEST FIT AT:  X= 65857  Y= 65381  Z=  2034
                 65864     65385      2041

          CH  30 CH  27 CH  26 CH  32 CH  36 CH  24 CH  20 CH  28
ACTUAL EVENT      0  4895  4900  5325  5555  5615  5970  6160
BLOCK  EVENT      0. 5057. 5445. 5217. 5108. 5376. 6930. 5927.

          CH  31 CH  25 CH  19 CH  22 CH
ACTUAL EVENT    6520  6650  6805  7140
BLOCK  EVENT    6062. 6513. 7453. 7415.

CHANNELS OUT ARE : 20

"S" WAVE CHANNELS ARE :  27 26 32 36 24 20 28 31 25 19 22

   ERROR ERS     =   13.7



   EVENT:  EV  JD YR  TIME        BLOCK INCREMENT   VELOCITY
         25 266 91 21:52              5.      6100.- 3700.
                 65805     65457      2296
   BEST FIT AT:  X= 65808  Y= 65460  Z=  2308
                 65818     65470      2309

          CH  30 CH  33 CH  24 CH  20 CH  40 CH  13 CH  27 CH   3
ACTUAL EVENT      0   390   630  2080  2120  2735  2810  3820
BLOCK  EVENT      0.  209. 2403.  952.  975. 2591. 2442. 4217.

          CH  18 CH   5 CH   1 CH  29 CH
ACTUAL EVENT    4500  4880  5020  6915
BLOCK  EVENT    4567. 4722. 4148. 4368.

CHANNELS OUT ARE : 24 20 40 27  1 29

"S" WAVE CHANNELS ARE :  24 40 27 29

   ERROR ERS     =   13.4
```

EVENT: EV JD YR TIME BLOCK INCREMENT VELOCITY
26 273 91 22: 3 5. 6100.- 3700.
64762 66082 2214
BEST FIT AT: X= 64762 Y= 66094 Z= 2223
64775 66095 2227

	CH 25	CH 19	CH 33	CH 26	CH 20
ACTUAL EVENT	0	120	1020	1980	2270
BLOCK EVENT	0.	472.	1252.	1985.	1918.

ERROR ERS = 16.8

APPENDIX D

Source Location - Simplex Algorithm

```
   EVENT:  EV  JD YR  TIME          VELOCITY
           1  65 91 11:51          6100.- 3700.

BEST FIT AT:  X= 65601  Y= 65436  Z=  2686

            CH  11 CH  33 CH  31 CH  19 CH  12 CH  18 CH
ACTUAL EVENT      0  1955  3055  3200  3555  8385
BLOCK  EVENT      0.  1676.  3279.  1413.  3748.  8548.

CHANNELS OUT ARE : 19

"S" WAVE CHANNELS ARE :  31 19 12 18

   ERROR ERS     =    13.4



   EVENT:  EV  JD YR  TIME          VELOCITY
           2  65 91 22:49          6100.- 3700.

   BEST FIT AT:  X= 65795  Y= 65593  Z=  2577

            CH  23 CH   8 CH  31 CH  25 CH  29 CH  19 CH  26 CH   9
ACTUAL EVENT      0   335   935  1060  1085  1315  1530  1860
BLOCK  EVENT      0.   436.  1011.  1112.   725.  1371.  1539.  1897.

            CH  17 CH  11 CH  33 CH  12 CH
ACTUAL EVENT   2200  2230  2310  2465
BLOCK  EVENT   1343.  2213.  2327.  2480.

CHANNELS OUT ARE : 29 17

   ERROR ERS     =    3.2
```

EVENT: EV JD YR TIME VELOCITY
3 66 91 0:52 6100.- 3700.

BEST FIT AT: X= 65580 Y= 65508 Z= 2649

	CH 31	CH 29	CH 22	CH 18	CH 16
ACTUAL EVENT	0	2125	8455	9075	9470
BLOCK EVENT	0.	2180.	8556.	9105.	9455.

"S" WAVE CHANNELS ARE : 29 22 18 16

ERROR ERS = 3.7

```
   EVENT:  EV  JD YR  TIME          VELOCITY
           4 123 91 22:36          6100.- 3700.

   BEST FIT AT:  X= 65783  Y= 65393  Z=  2564

          CH  35 CH  26 CH  32 CH  20 CH  33 CH  36 CH  10 CH  19
ACTUAL EVENT      0   200   825  1150  1280  1345  1895  1900
BLOCK  EVENT      0.  212.  792. 1120. 1350. 1144. 1932. 1917.

          CH  12 CH  21 CH  31 CH  25 CH
ACTUAL EVENT    1905  1985  2180  2325
BLOCK  EVENT    1804. 1316. 2109. 2053.

CHANNELS OUT ARE : 21

   ERROR ERS      =     7.2



   EVENT:  EV  JD YR  TIME          VELOCITY
           5 123 91 22:37          6100.- 3700.

   BEST FIT AT:  X= 65756  Y= 65410  Z=  2573

          CH  33 CH  32 CH  31 CH  10 CH  30 CH  13 CH  11 CH  23
ACTUAL EVENT      0   275   330   770  1150  1815  1855  1900
BLOCK  EVENT      0.  101.  584.  893. 1226. 3639. 3204. 1894.

          CH  29 CH   8 CH   1 CH   9 CH
ACTUAL EVENT    1945  2020  2045  2110
BLOCK  EVENT    1989. 3641. 2671. 2149.

CHANNELS OUT ARE : 32 13 11  8  1

"S" WAVE CHANNELS ARE :  32 13 11  8

   ERROR ERS      =     7.4



   EVENT:  EV  JD YR  TIME          VELOCITY
           6 123 91 23: 7          6100.- 3700.

   BEST FIT AT:  X= 65761  Y= 65389  Z=  2506

          CH  35 CH  26 CH  32 CH  20 CH  33 CH  36 CH  31 CH  25
ACTUAL EVENT      0    85   470   765  1000  1675  1770  1790
BLOCK  EVENT      0.   75.  439. 1140.  846.  834. 1721. 1754.

          CH  19 CH  12 CH  10 CH  21 CH
ACTUAL EVENT    1810  2545  2865  3180
BLOCK  EVENT    1843. 2498. 2735. 1415.
```

CHANNELS OUT ARE : 20 36 21

ERROR ERS = 4.8

EVENT: EV JD YR TIME VELOCITY
6 123 91 23: 7 6100.- 3700.

BEST FIT AT: X= 65750 Y= 65381 Z= 2519

	CH 35	CH 26	CH 32	CH 20	CH 33	CH 36	CH 31	CH 25
ACTUAL EVENT	0	85	470	765	1000	1675	1770	1790
BLOCK EVENT	114.	0.	540.	1036.	795.	1917.	1837.	1835.

	CH 19	CH 12	CH 10	CH 21
ACTUAL EVENT	1810	2545	2865	3180
BLOCK EVENT	1855.	2467.	2834.	1343.

CHANNELS OUT ARE : 26 36 21

"S" WAVE CHANNELS ARE : 36

ERROR ERS = 8.3

EVENT: EV JD YR TIME VELOCITY
7 123 91 23:15 6100.- 3700.

BEST FIT AT: X= 65732 Y= 65344 Z= 2366

	CH 35	CH 33	CH 32	CH 40	CH 26	CH 20	CH 36	CH 31
ACTUAL EVENT	0	45	140	975	980	1065	1195	1210
BLOCK EVENT	0.	145.	340.	1115.	222.	980.	11.	1118.

	CH 25	CH 41	CH 19	CH 21
ACTUAL EVENT	1265	1380	1705	1730
BLOCK EVENT	1272.	1271.	1620.	989.

CHANNELS OUT ARE : 26 36 21

ERROR ERS = 7.0

EVENT: EV JD YR TIME VELOCITY
8 141 91 21:54 6100.- 3700.

BEST FIT AT: X= 65665 Y= 65455 Z= 2638

	CH 19	CH 25	CH 31	CH 26	CH 33	CH 32	CH 20	CH 9
ACTUAL EVENT	0	480	935	1075	1335	2175	2850	2980
BLOCK EVENT	0.	704.	1017.	1105.	1349.	1977.	1943.	2897.

	CH 17	CH 10	CH 11	CH 8
ACTUAL EVENT	3630	4365	4370	4600
BLOCK EVENT	1960.	4487.	1730.	3852.

CHANNELS OUT ARE : 20 17 11 8

"S" WAVE CHANNELS ARE : 32 20 9 17 10 11 8

ERROR ERS = 8.0

```
   EVENT:  EV  JD YR  TIME          VELOCITY
           9 141 91 21:54          6100.- 3700.

   BEST FIT AT:  X= 65476  Y= 65414  Z=  2552

          CH  32 CH   9 CH  29 CH  35 CH   8 CH  10 CH  20 CH  31
ACTUAL EVENT      0   410   965   990  2560  2680  2945  2965
BLOCK  EVENT      0.  523.  376.  1623. 2415. 2883. 1971. 1213.

          CH  36 CH  18 CH  14 CH   1 CH
ACTUAL EVENT   4110  4495  5040  5440
BLOCK  EVENT   4148. 4492. 5012. 8480.

CHANNELS OUT ARE : 29 35 20 31  1

"S" WAVE CHANNELS ARE :  20 31 36 18 14  1

   ERROR ERS     =    6.9
```

EVENT: EV JD YR TIME VELOCITY
10 143 91 20:31 6100.- 3700.

BEST FIT AT: X= 65579 Y= 65119 Z= 2961

	CH 7	CH 29	CH 6	CH 4	CH 14	CH 16	CH 2	CH 18
ACTUAL EVENT	0	485	1185	1665	2080	2205	5900	9100
BLOCK EVENT	0.	7982.	1060.	1544.	2015.	1950.	5728.	7506.

CHANNELS OUT ARE : 29 18

"S" WAVE CHANNELS ARE : 2 18

ERROR ERS = 9.8

EVENT: EV JD YR TIME VELOCITY
11 144 91 3:55 6100.- 3700.

BEST FIT AT: X= 65630 Y= 65171 Z= 2895

	CH 7	CH 6	CH 4	CH 14	CH 16	CH 2	CH 18	CH 15
ACTUAL EVENT	0	1295	1630	2095	2205	2860	4540	5195
BLOCK EVENT	0.	1261.	1683.	2088.	2303.	2863.	4518.	5228.

ERROR ERS = 2.8

EVENT: EV JD YR TIME VELOCITY
12 144 91 17:55 6100.- 3700.

BEST FIT AT: X= 65615 Y= 65510 Z= 2720

	CH 9	CH 11	CH 19	CH 25	CH 0	CH 8	CH 31	CH 23
ACTUAL EVENT	0	490	1790	1895	1900	2070	2135	2635
BLOCK EVENT	0.	769.	1496.	2069.	2226.	2227.	2369.	2788.

	CH 29	CH 32	CH 10	CH 4
ACTUAL EVENT	2645	2875	3350	3520
BLOCK EVENT	2757.	2828.	3332.	3499.

CHANNELS OUT ARE : 19

ERROR ERS = 11.1

EVENT: EV JD YR TIME VELOCITY
12 144 91 17:55 6100.- 3700.

BEST FIT AT: X= 65619 Y= 65514 Z= 2718

	CH 9	CH 11	CH 19	CH 25	CH 0	CH 8	CH 31	CH 23
ACTUAL EVENT	0	490	1790	1895	1900	2070	2135	2635
BLOCK EVENT	0.	853.	1530.	2086.	2244.	2195.	2381.	2753.

	CH 29	CH 32	CH 10	CH 4
ACTUAL EVENT	2645	2875	3350	3520
BLOCK EVENT	2739.	2841.	3337.	3595.

CHANNELS OUT ARE : 11 19

ERROR ERS = 10.4

```
   EVENT:  EV  JD YR  TIME          VELOCITY
        13 149 91 21:54          6100.- 3700.
   BEST FIT AT:  X= 65561  Y= 65359  Z=  3073

          CH  2 CH  4 CH  15 CH  7 CH  0 CH  12 CH  9 CH  1
ACTUAL EVENT      0   260   940  4300  5455  6640  6700  7520
BLOCK  EVENT      0.  422.  871. 3996. 5122. 6932. 6742. 5673.

          CH  20 CH  19 CH  11 CH  8 CH
ACTUAL EVENT    7905  7945  8010  8280
BLOCK  EVENT    9090. 9173. 5973. 8393.

CHANNELS OUT ARE :  1 20 19 11

"S" WAVE CHANNELS ARE :   7 64 12  9  1 20 19 11  8

   ERROR ERS      =    13.3



   EVENT:  EV  JD YR  TIME          VELOCITY
        13 149 91 21:54          6100.- 3700.

   BEST FIT AT:  X= 65552  Y= 65335  Z=  3048

          CH  2 CH  4 CH  15 CH  7 CH  0 CH  12 CH  9 CH  1
ACTUAL EVENT      0   260   940  4300  5455  6640  6700  7520
BLOCK  EVENT      0.  346. 1098. 3459. 5430. 6738. 6765. 5856.

          CH  20 CH  19 CH  11 CH  8 CH
ACTUAL EVENT    7905  7945  8010  8280
BLOCK  EVENT    8754. 8965. 5810. 8538.

CHANNELS OUT ARE :  7  1 20 19 11

"S" WAVE CHANNELS ARE :   7 64 12  9  1 20 19 11  8

   ERROR ERS      =    8.4



   EVENT:  EV  JD YR  TIME          VELOCITY
        15 149 91 21:54          6100.- 3700.

   BEST FIT AT:  X= 65857  Y= 65559  Z=  2913

          CH  1 CH  0 CH  3 CH  10 CH  13 CH  5 CH  30 CH  9
ACTUAL EVENT      0   370   535  1535  1885  2775  3490  4140
BLOCK  EVENT      0.  193. 1114. 1455. 2705. 2549. 4190. 2725.

          CH  23 CH  32 CH  31 CH  29 CH
ACTUAL EVENT    4265  4935  6115  6335
```

BLOCK EVENT 4233. 4552. 4828. 4842.

CHANNELS OUT ARE : 3 13 30 9 31 29

ERROR ERS = 13.3

EVENT: EV JD YR TIME VELOCITY
16 163 91 21:43 6100.- 3700.

BEST FIT AT: X= 65744 Y= 65233 Z= 2657

	CH 21	CH 14	CH 12	CH 20	CH 13	CH 6	CH 26	CH 36
ACTUAL EVENT	0	720	3035	3290	3410	4145	4685	4795
BLOCK EVENT	0.	401.	2766.	3069.	3277.	4127.	3866.	2212.

	CH 11	CH 33	CH 5	CH 35
ACTUAL EVENT	5065	5130	5515	5695
BLOCK EVENT	5251.	4337.	5480.	3358.

CHANNELS OUT ARE : 26 36 33 35

"S" WAVE CHANNELS ARE : 12 20 13 6 26 36 11 33 5 35

ERROR ERS = 12.1

EVENT: EV JD YR TIME VELOCITY
17 168 91 22:26 6100.- 3700.

BEST FIT AT: X= 65807 Y= 65333 Z= 2635

	CH 35	CH 12	CH 13	CH 21	CH 36	CH 26	CH 20	CH 10
ACTUAL EVENT	0	190	230	430	675	680	825	830
BLOCK EVENT	0.	185.	203.	115.	569.	595.	777.	744.

	CH 32	CH 33	CH 14	CH 3
ACTUAL EVENT	1505	1515	1570	1860
BLOCK EVENT	1458.	1519.	1487.	1895.

CHANNELS OUT ARE : 21

ERROR ERS = 3.8

EVENT: EV JD YR TIME VELOCITY
18 169 91 21:54 6100.- 3700.

BEST FIT AT: X= 65686 Y= 65346 Z= 2797

	CH 4	CH 15	CH 11	CH 2	CH 0	CH 9	CH 12	CH 7
ACTUAL EVENT	0	220	445	780	905	1195	1350	1615
BLOCK EVENT	0.	2747.	998.	562.	2404.	2613.	707.	1621.

	CH 14	CH 10	CH 19	CH 20
ACTUAL EVENT	2010	2275	2415	2620
BLOCK EVENT	1170.	2208.	2790.	2174.

CHANNELS OUT ARE : 15 11 0 9 12 14

ERROR ERS = 17.1

EVENT: EV JD YR TIME VELOCITY
19 178 91 3:29 6100.- 3700.

BEST FIT AT: X= 65695 Y= 65457 Z= 2628

	CH 32	CH 26	CH 20	CH 11	CH 33	CH 12	CH 8	CH 9
ACTUAL EVENT	0	80	195	325	560	975	980	995
BLOCK EVENT	0.	200.	259.	414.	723.	1033.	1165.	1126.

	CH 10	CH 36	CH 21	CH 23
ACTUAL EVENT	1305	1725	2090	2235
BLOCK EVENT	1430.	1865.	1645.	1597.

CHANNELS OUT ARE : 21 23

ERROR ERS = 7.7

EVENT: EV JD YR TIME VELOCITY
20 180 91 8:19 6100.- 3700.

BEST FIT AT: X= 65703 Y= 65054 Z= 2729

	CH 16	CH 22	CH 14	CH 7	CH 21	CH 18	CH 36	CH 20
ACTUAL EVENT	0	1890	1895	2115	3230	3300	3665	4495
BLOCK EVENT	0.	1722.	1840.	2006.	3048.	3228.	3686.	4300.

	CH 26	CH 6	CH 33	CH 4
ACTUAL EVENT	4975	4980	5050	5865
BLOCK EVENT	4996.	1884.	4944.	3539.

CHANNELS OUT ARE : 6 4

ERROR ERS = 7.4

EVENT: EV JD YR TIME VELOCITY
21 181 91 9:34 6100.- 3700.

BEST FIT AT: X= 65740 Y= 65069 Z= 2751

	CH 16	CH 22	CH 7	CH 14	CH 6	CH 21	CH 18	CH 4
ACTUAL EVENT	0	2010	2140	2675	3095	3415	3550	4370
BLOCK EVENT	0.	1931.	2035.	1974.	1551.	3217.	4078.	3443.

	CH 20	CH 26	CH 33	CH 32
ACTUAL EVENT	4625	5255	5425	6270
BLOCK EVENT	4518.	5165.	5251.	6171.

CHANNELS OUT ARE : 14 6 18 4

ERROR ERS = 7.9